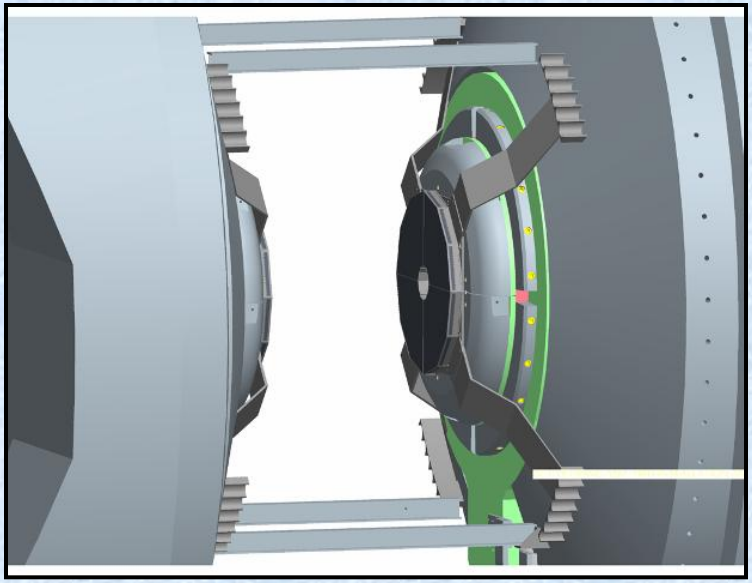
The Physics of the Reaction Plane Detector



Abby Bickley

University of Colorado

February 6, 2007

Questions

1. What does the reaction plane detector actually measure?
2. How is this incorporated into physics analyses?
3. What do these measurements allow us to learn about the collision medium?

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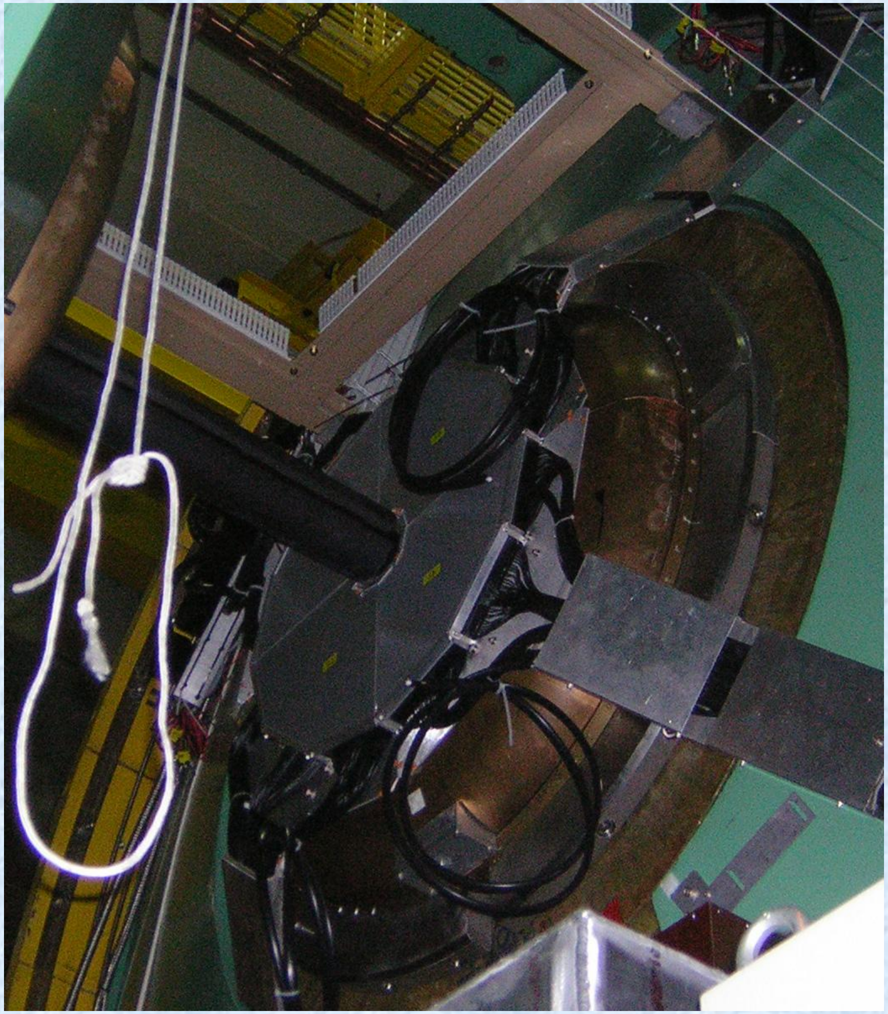
The Reaction Plane Detector

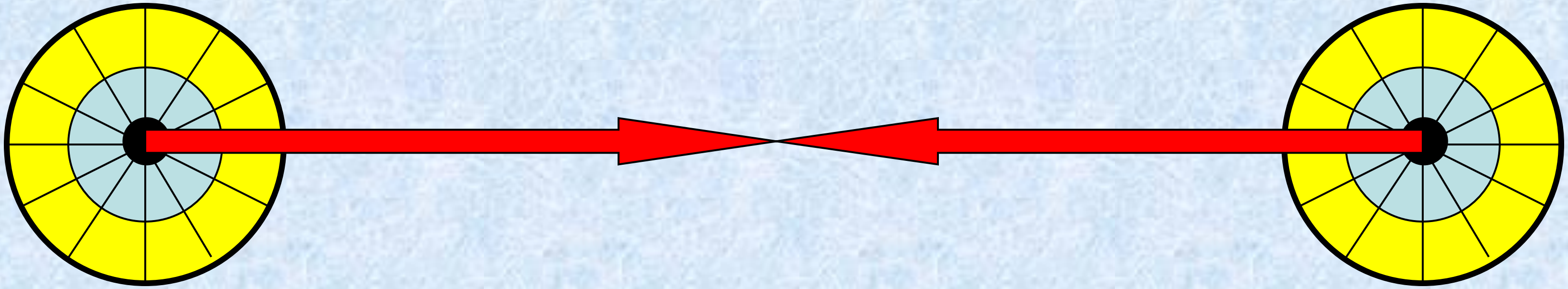
- Review from last week:
  - Two sets of plastic scintillators positioned on either side of the collision vertex ($38 < |z| < 40$cm)
  - 12 segments in ϕ
  - 2 segments in η
    - $1.0 < |\eta| < 1.5$
    - $1.5 < |\eta| < 2.8$



What does the reaction plane detector measure?

- As charged particles pass through the plastic scintillator they deposit energy and photons are produced
- These photons are collected and amplified by PMT’s
- Resulting signal is proportional to the original energy deposition in each individual segment

What does the reaction plane detector measure?



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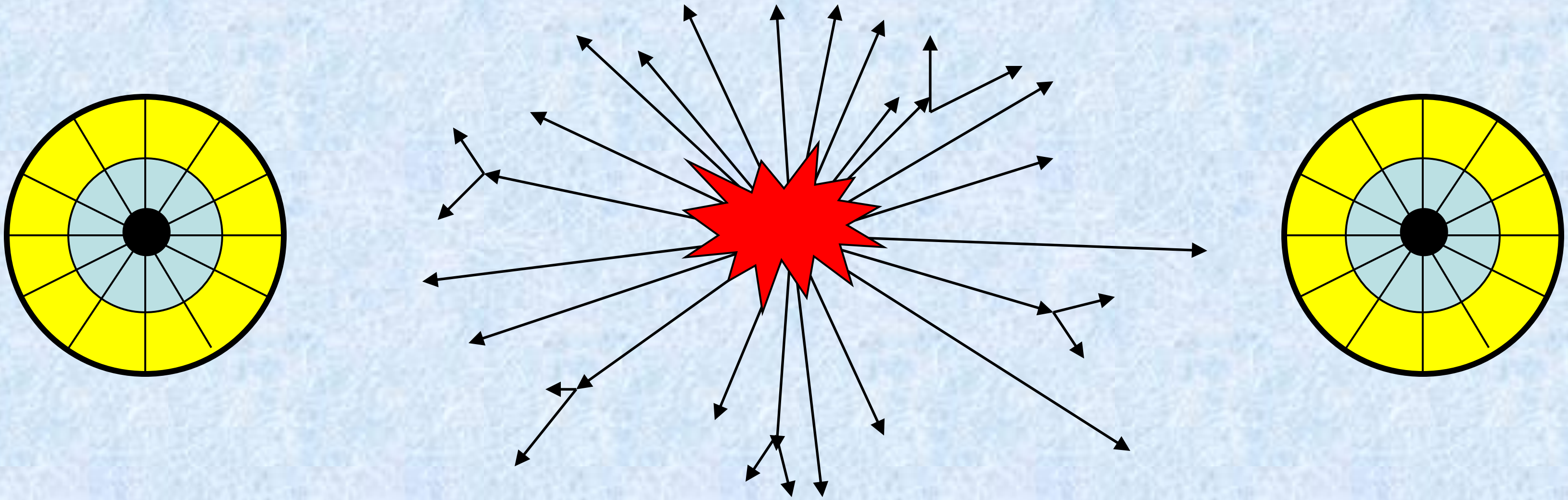

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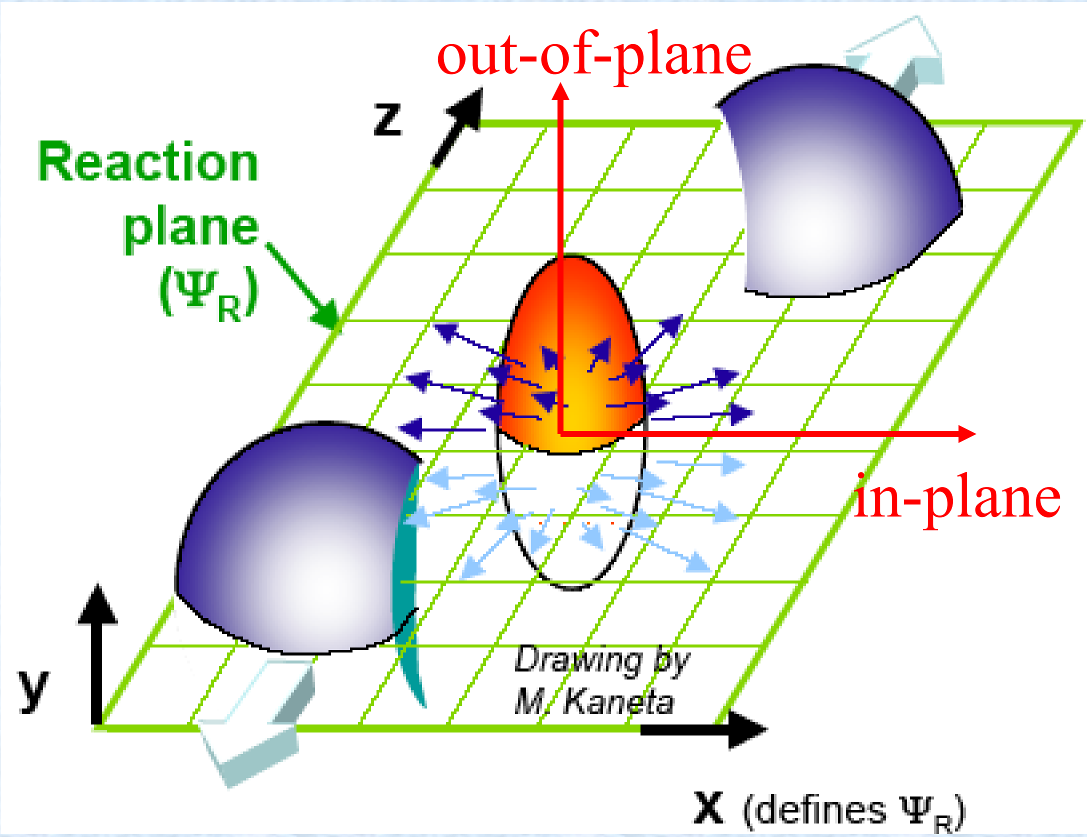
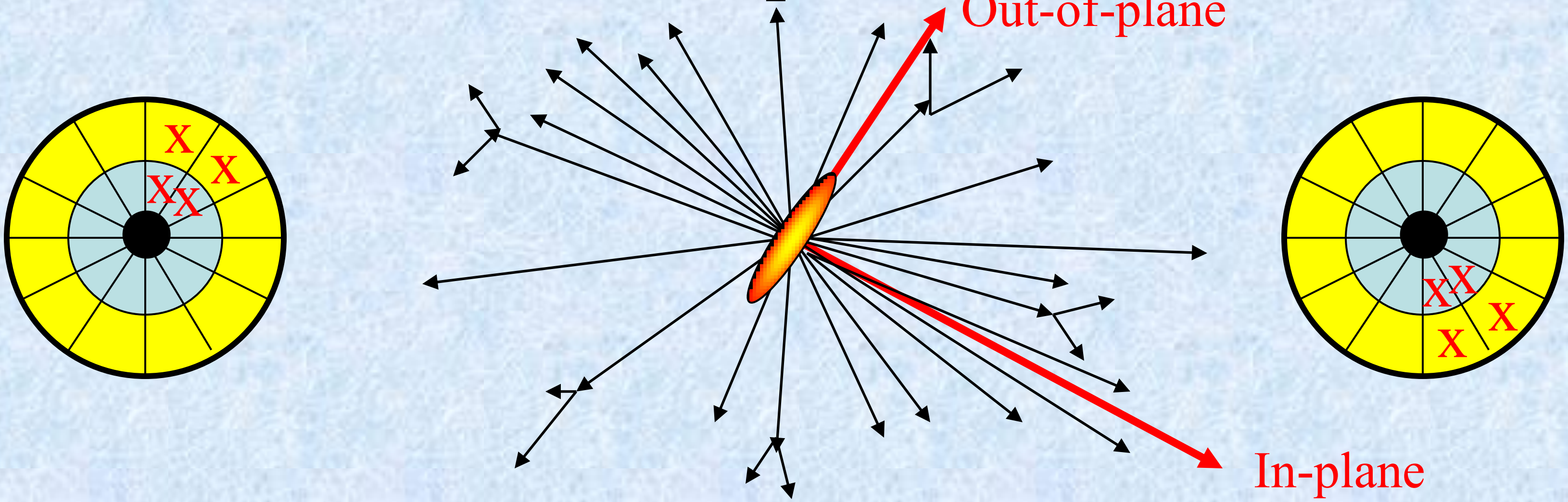
Reaction Plane Definition



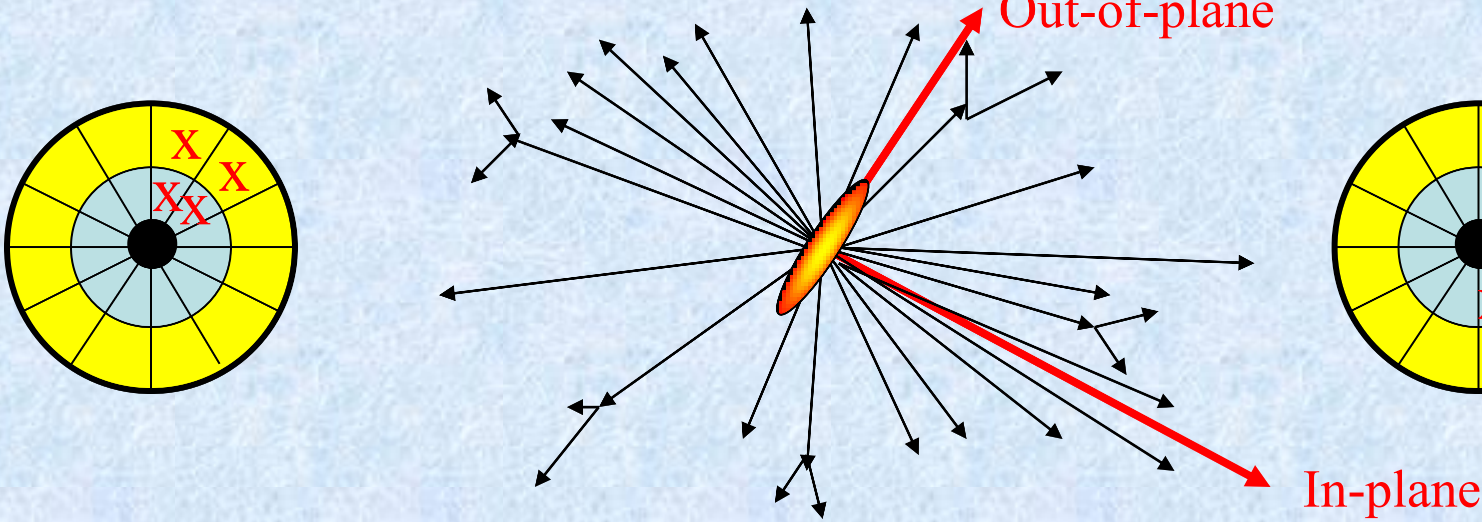
- Incomplete overlap between nuclei results in an “almond” shaped collision region
- Characterize collision region by reaction plane (defined by beam direction and vector between centers of colliding nuclei)
- Pressure gradient to expand is greatest along short axis (in-plane)
- Results in greater particle emission in-plane

What does the reaction plane detector measure?



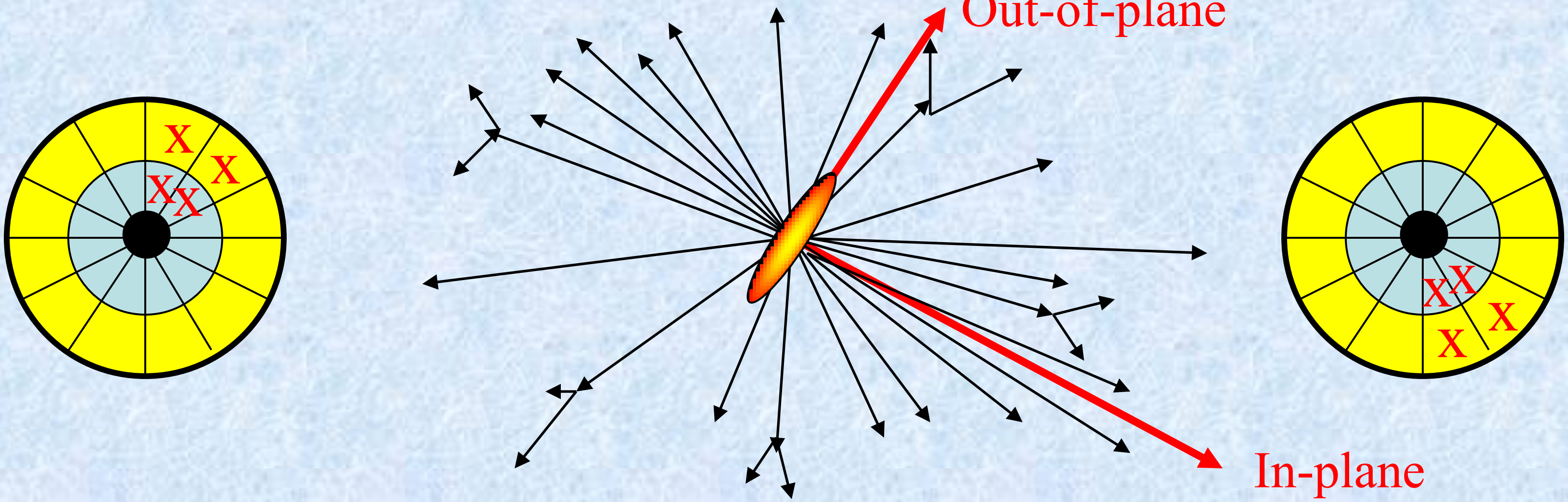
- In non-central collisions the difference between the in-plane and out-of-plane pressure gradients results in preferential in-plane particle emission
- This shows up in the reaction plane detector as an increased energy deposition in those segments aligned with the reaction plane
- Allows for an event-by-event determination of Ψ_R

Measurement Limitations



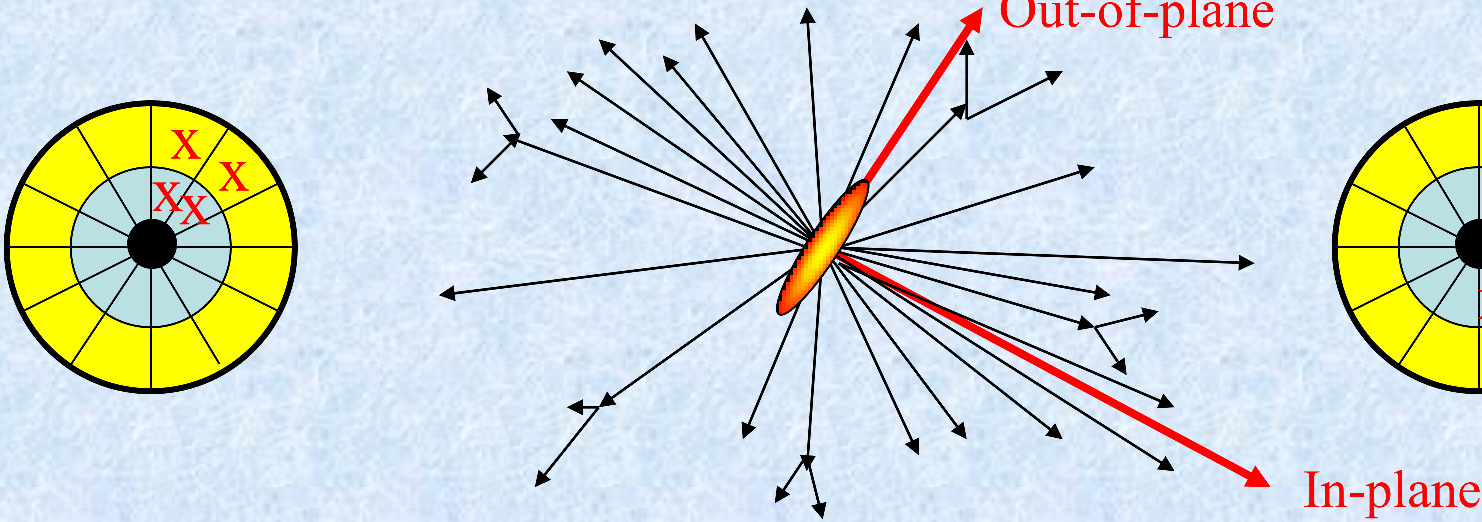
1. Back to back jets:
   – Create a spray of particles at 180˚
   – Could mask or bias preferential angle of emission by pressure gradients
   – Preferentially generated in mid-rapidity region ∴ would only influence Ψ_R determination in outer scintillator segments
2. Collision centrality
3. Reaction plane resolution

Measurement Limitations



1. Back to back jets:
2. Collision centrality:
   - The more central the collision the more spherical the overlap region and weaker the difference in the pressure gradients
   - Hence ability to determine Ψ_R is highly dependent on the collision centrality
3. Reaction plane resolution

Measurement Limitations



1. Back to back jets:
2. Collision centrality:
3. Reaction plane resolution:
   – Correction factor that is applied to account for the fact that the finite number of particles used to determine the reaction plane result in a limited resolution in the angle of the measured reaction plane

Reaction Plane Resolution

- Method 1: Direct Calculation

$$\sigma_{RP} = \left\langle \cos\left[n\left(\psi_{\mathrm{expt}} - \Psi_{\mathrm{true}}\right)\right]\right\rangle$$

A priori
not known

Reaction Plane Resolution

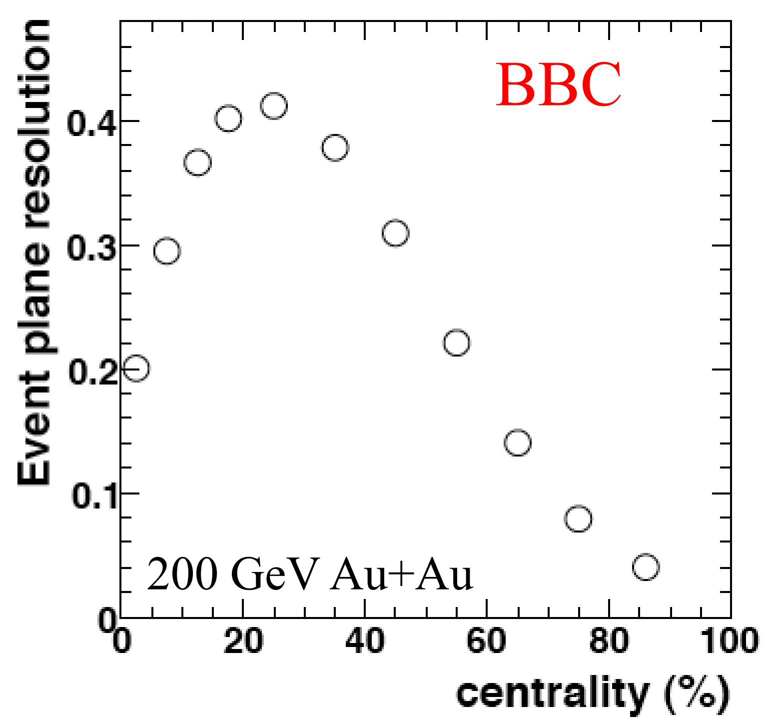
- Method 2: Sub-event method
  - Use two independent sets of particles (a,b) from the same event to calculate the reaction plane
  - Compare reaction plane from each sub-event to determine resolution

$$\sigma_{RP} = \sqrt{\left\langle \cos\left[n\left(\psi_n^a - \psi_n^b\right)\right]\right\rangle}$$

  - Requires assumptions:
    - Both sub-events contain the same number of particles
    - Degree of flow is the same in each sub-event
    - Any particle correlations other than flow are negligible

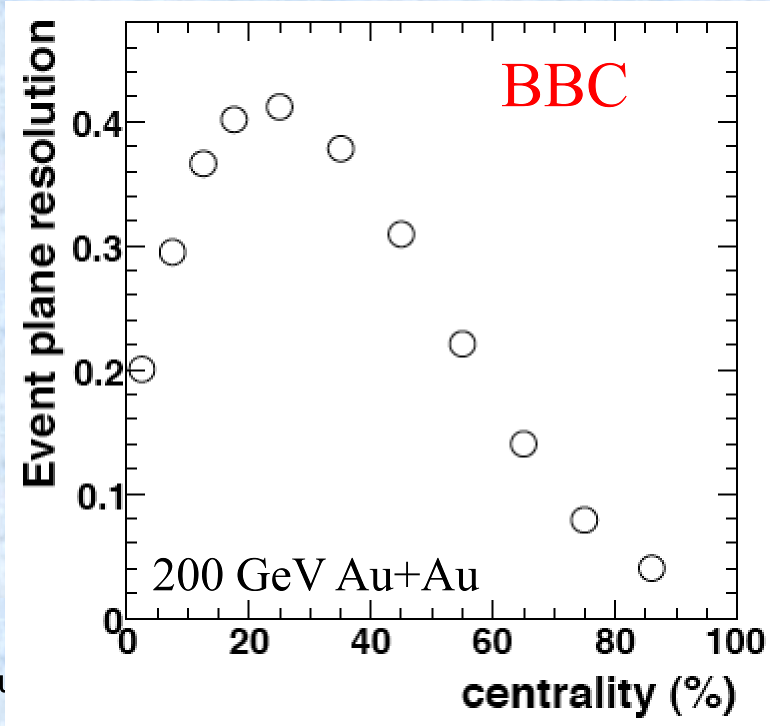
Reaction Plane Resolution

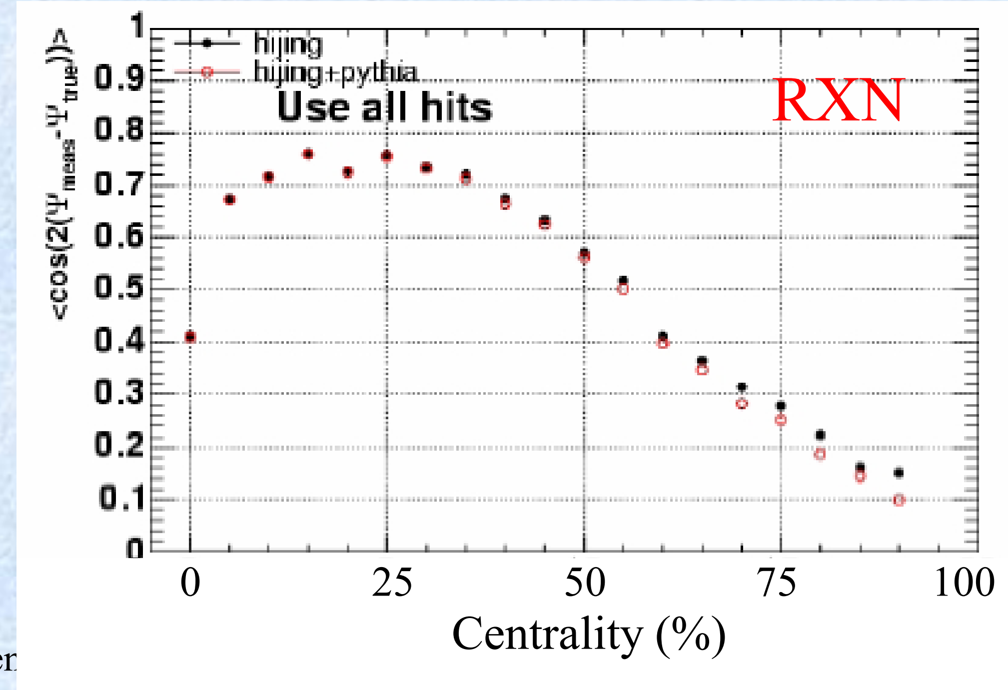
- Method 2: Sub-event method application
  - Each set of BBC's compose a single sub-event
  - BBC's are symmetric in acceptance so it is reasonable to assume both sub-events contain the same number of particles and degree of flow
  - BBC's are far forward in rapidity thus any particle correlations other than flow are negligible (3.1 < |η| < 3.9)



Reaction Plane Resolution

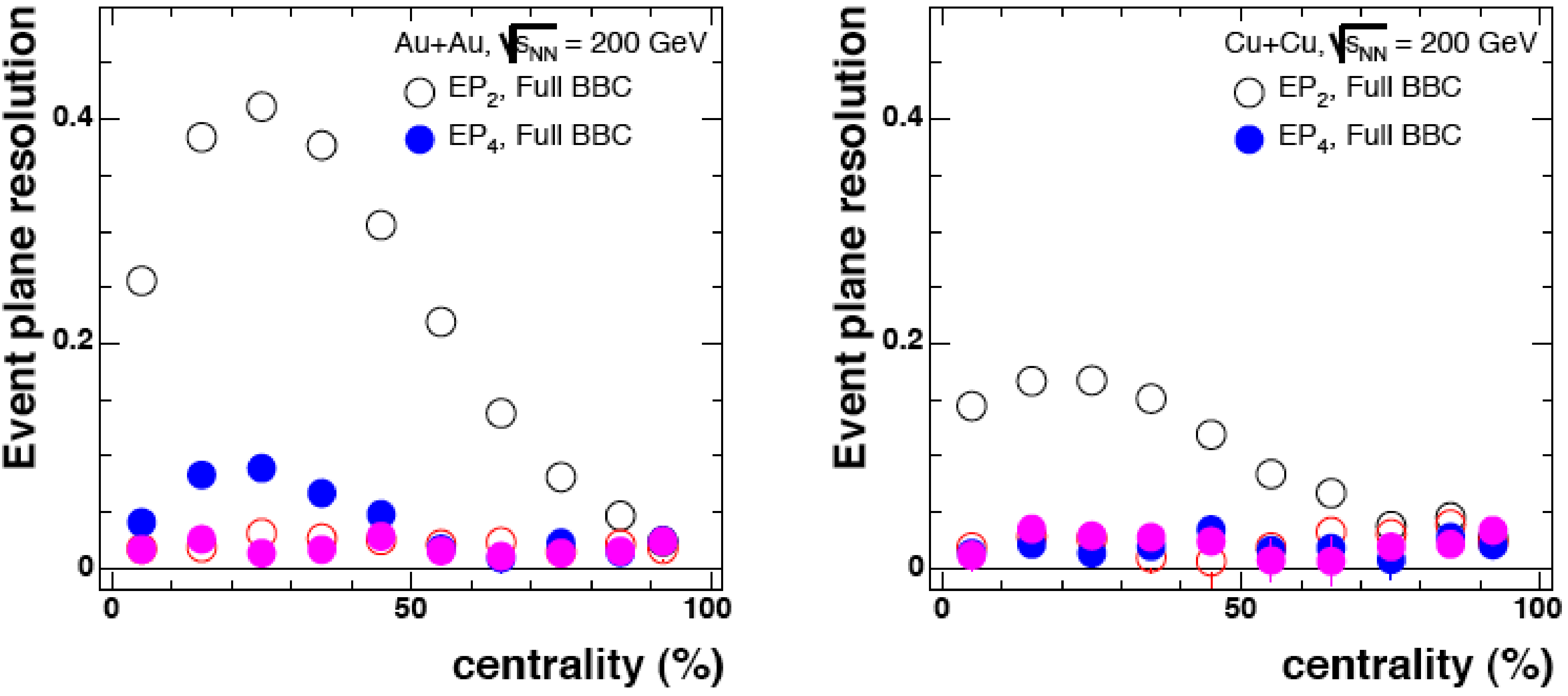
- Method 2: Sub-event method application
  - Same technique can be applied using the reaction plane detector
  - Rapidity coverage is greater $1.0<|\eta|<2.8$ compared to $3.1<|\eta|<3.9$ of BBC's
  - Incident multiplicity is greater
  - Pb converter enhances signal by converting neutrals to charged particles that can be detected in the scintillators





Reaction Plane Resolution

- Ability to determine reaction plane is dependent upon BBC incident multiplicity
- Beams of light ions and low energies result in fewer particles
- Future measurements of v_2 in these systems will require an improved reaction plane resolution



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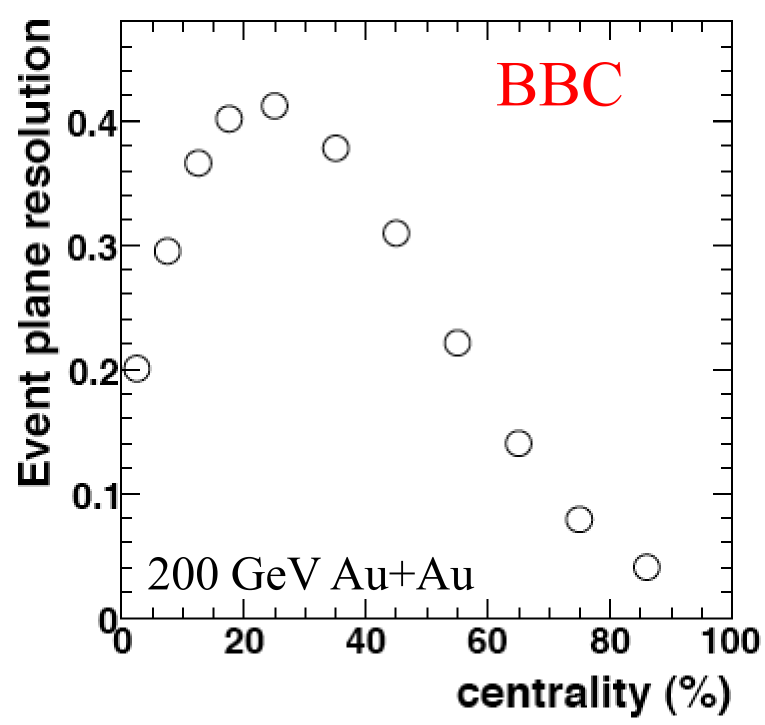

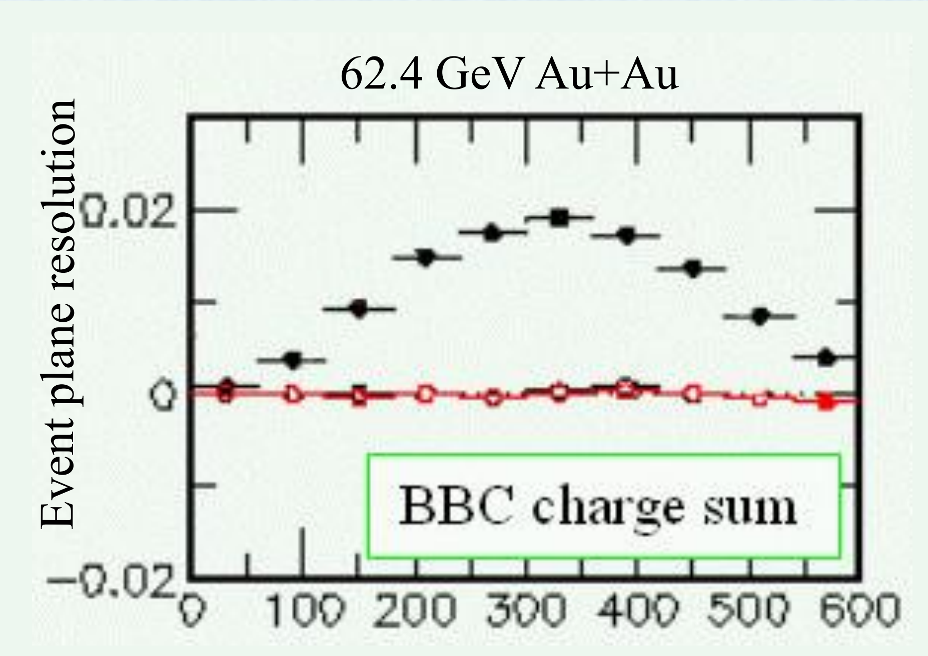

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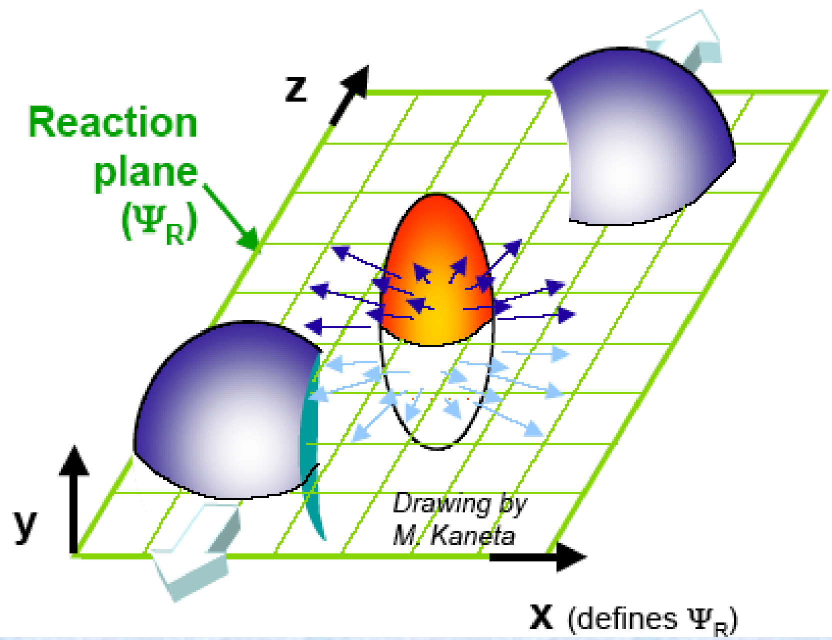
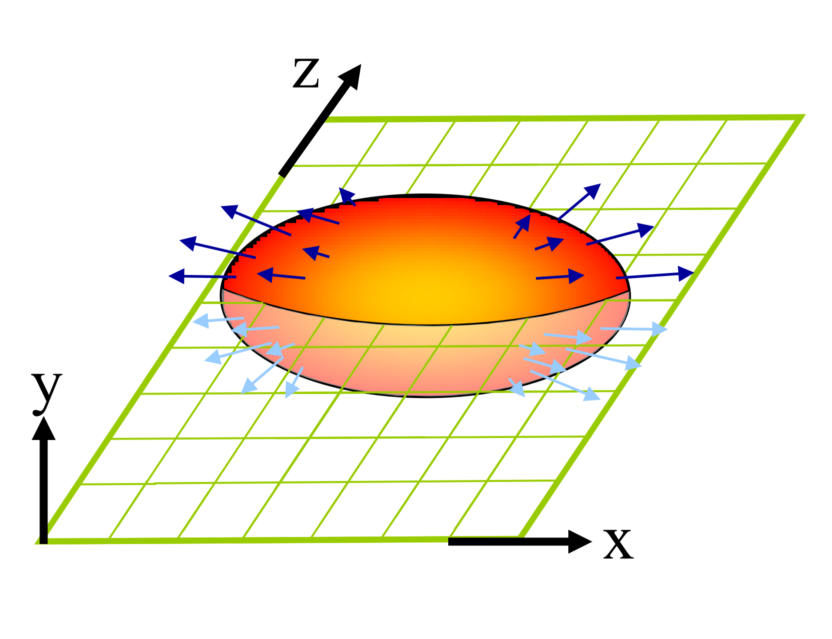
Azimuthal Anisotropy



time



1. Collision Feature ⇒ degree of overlap in colliding nuclei
2. Scattering converts spatial anisotropy to momentum anisotropy
3. Measurable Quantity ⇒ momentum anisotropy of produced particles

$$\frac{dN}{d(\psi - \Psi_{true})} \propto 1 + 2v_1 \cos(\varphi - \Psi_R) + 2v_2 \cos(2(\varphi - \Psi_R)) + \ldots$$

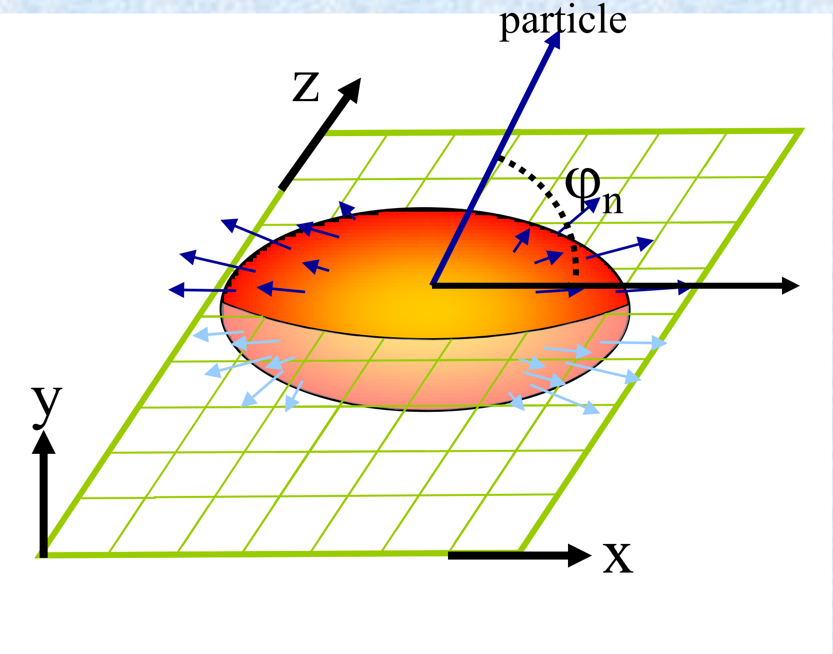
Directed Flow **Elliptic Flow**

Measuring Elliptic Flow

$$v_2^{meas} = \langle \cos(2\varphi) \rangle$$

φ = angle of each particle wrt reaction plane

- Elliptic Flow:
  - Second harmonic coefficient of the Fourier expansion of the azimuthal distribution of particles
  - $v_2 = \langle \cos(2\varphi_n) \rangle$.
- For each collision event determine reaction plane
- Measure angular distribution of emitted particles wrt reaction plane, φ_n
- Calculate v_2 per event
- Examine dependence on centrality, momentum, particle id, rapidity, collision energy, collision species….



Reaction Plane Resolution

$$v_2^{true} = \frac{\langle \cos[2(\varphi)] \rangle}{\sigma_{RP}}$$

$$v_2^{true} = \frac{\langle \cos[2(\varphi)] \rangle}{\sqrt{\langle \cos[2(\psi_2^a - \psi_2^b)] \rangle}}$$

- Resolution must be applied as a correction factor to any experimental measurement of flow
- Always results in $v_2^{true} > v_2^{meas}$
- The precision to which the reaction plane can be determined directly limits any measurement of flow and translates into the statistical error

Error Analysis

$$\delta\left(v_2^{\text{expt}}\right) \approx \frac{1}{\sqrt{N_{signal}}}$$

$$\delta\left(v_2^{\text{true}}\right) = \frac{\delta\left(v_2^{\text{expt}}\right)}{\sigma_{RP}} \approx \frac{1}{\sigma_{RP}\sqrt{N_{signal}}}$$

- The two key components of the statistical error in any elliptic flow measurements are the signal strength and the reaction plane resolution
- Statistical power of measured v_2 is reduced by $(\sigma_{RP})^2$
- Improvement provided by reaction plane detector compared to BBC's:

$$\left(\frac{\sigma_{RP}^{RXN}}{\sigma_{RP}^{BBC}}\right)^2 = \left(\frac{0.40}{0.70}\right)^2 \approx 3$$

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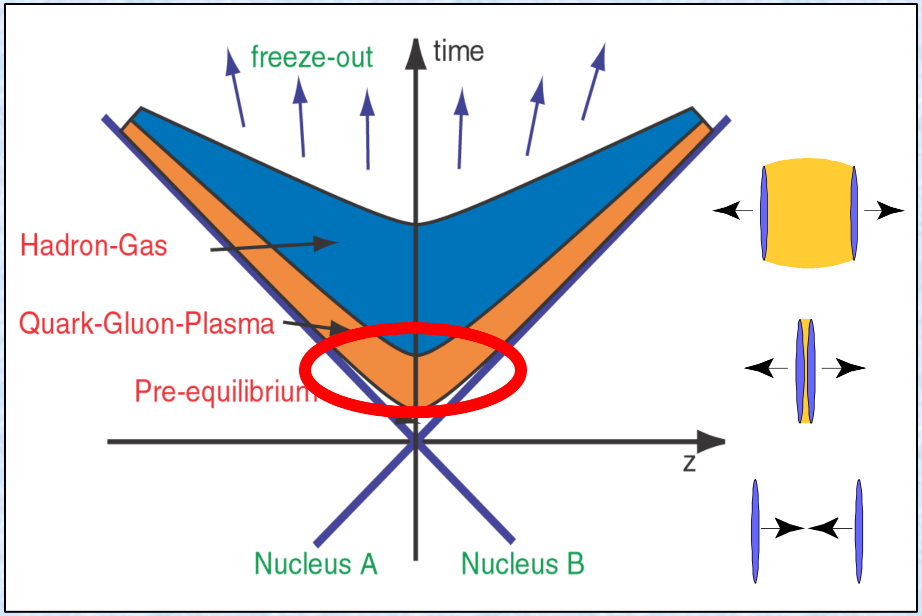
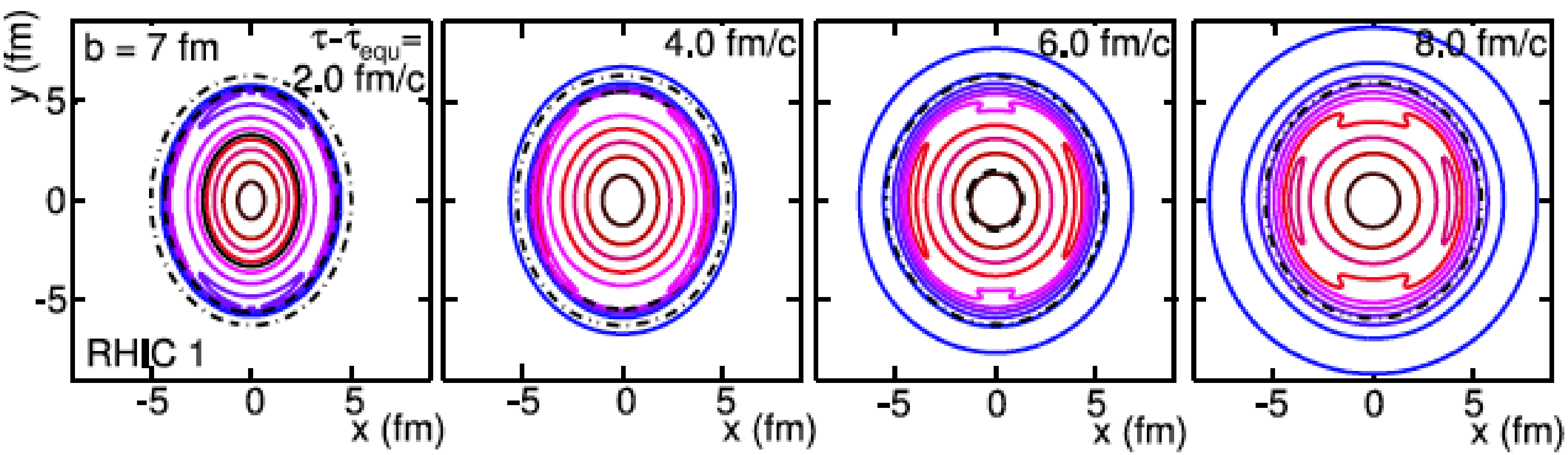
Collision Evolution



- Elliptic flow studies probe the early stages of the collision when the initial collision geometry still dominates
- System can be described by thermodynamic quantities only if thermal equilibrium is achieved
- This occurs during a heavy ion collision when the energy deposited during the collision generates large numbers of particles that interact & rescatter among themselves

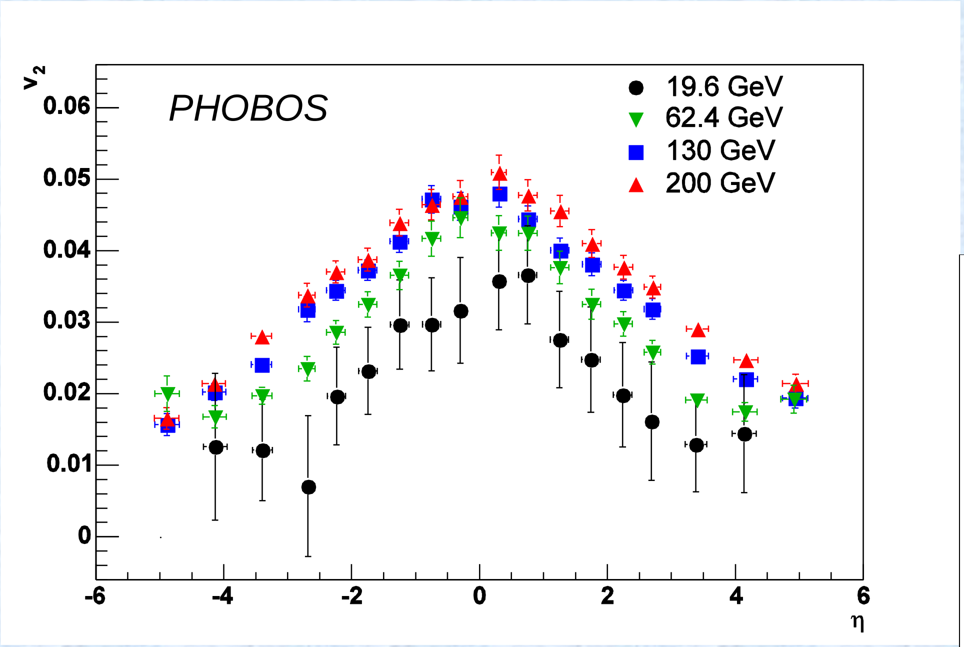
Time Scales



130GeV Au+Au Kolb & Heinz, nucl-th/0305084

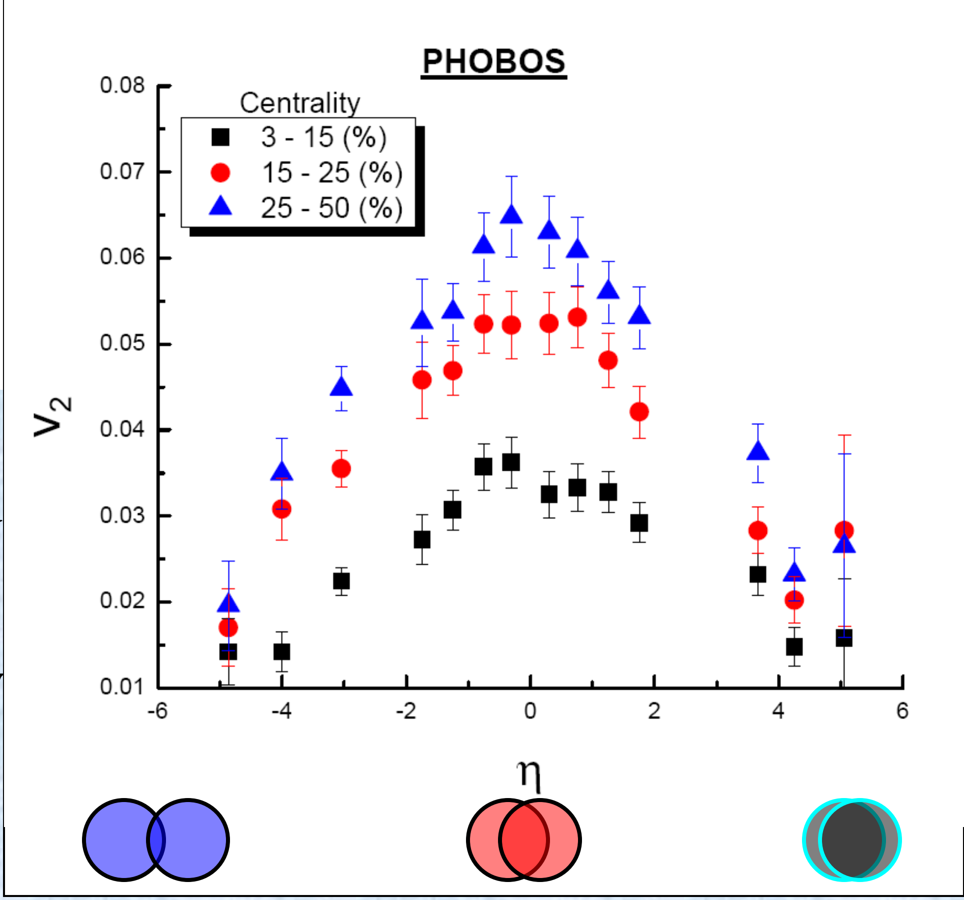
- Hydrodynamical models are used to calculate the time evolution of the energy density in-plane
- If thermal equilibrium is achieved:
  - late then asymmetry will be small
  - early then asymmetry will be large
- Experimental observation of v_2 implies local thermal equilibrium achieved while spatial anisotropy exists (ie short time scale)

Early Elliptic Flow Results



Centrality:

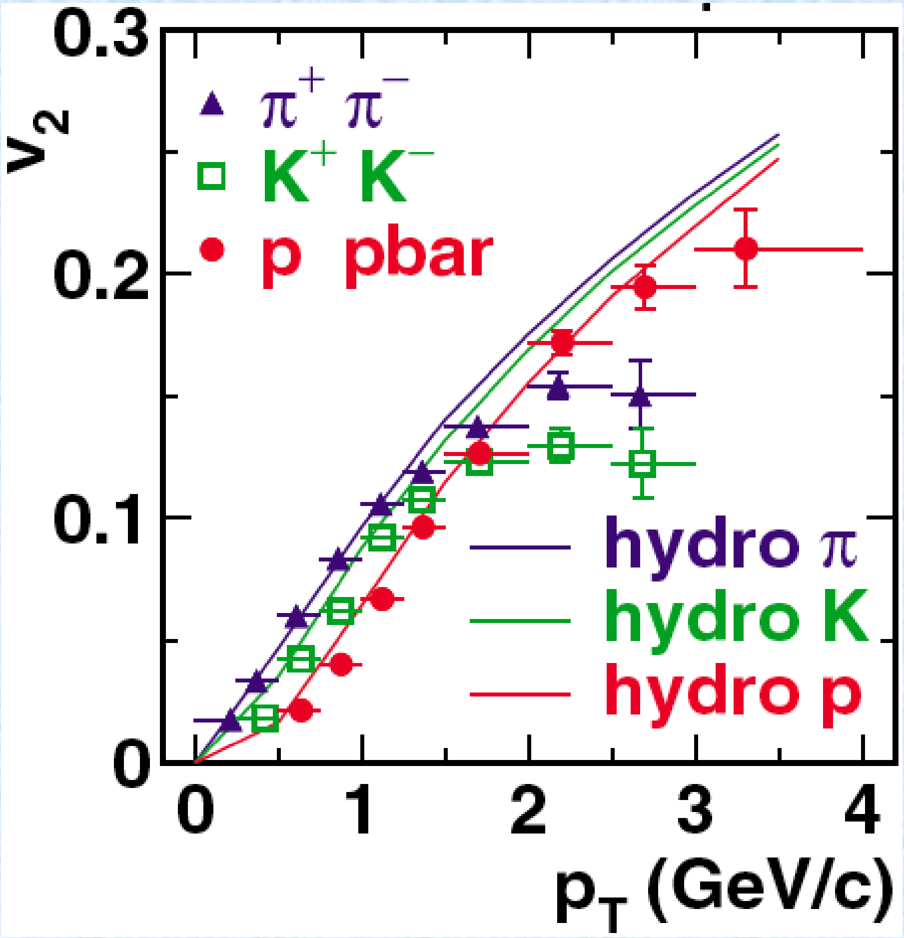
As % centrality decreases overlap region becomes less asymmetric ∴ less difference in pressure gradient



Collision Energy:

As collision energy decreases energy density pressure gradient also decreases resulting in decreased flow

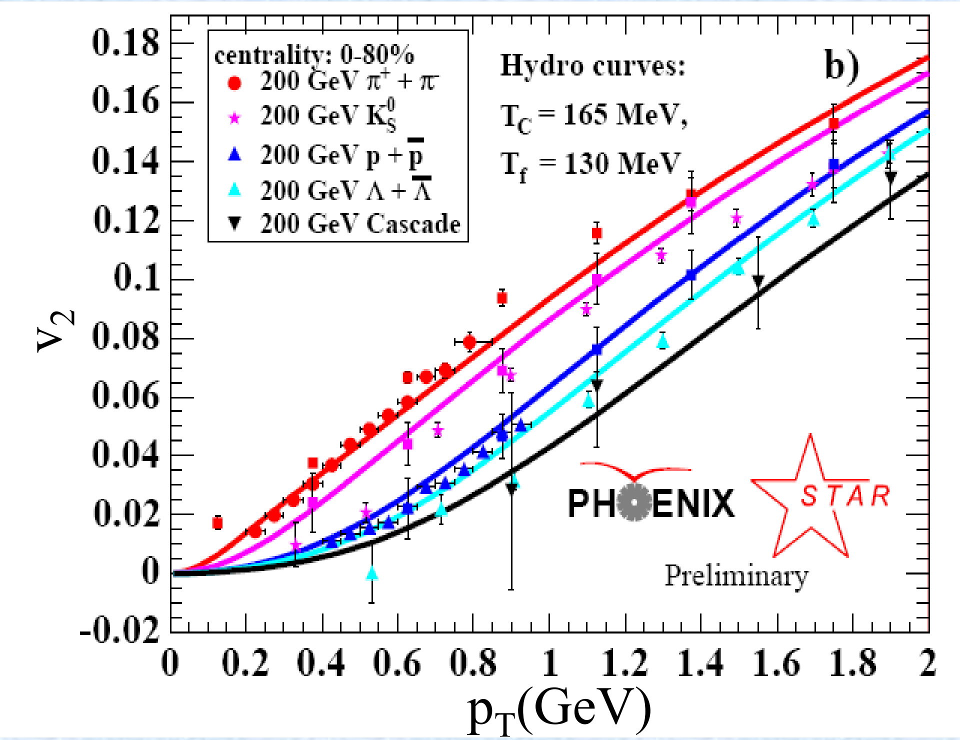
Early Elliptic Flow Results



White Paper Conclusions:

- Identified hadron v_2 is well reproduced by hydro calculations at low p_T
- Magnitude of v_2 requires thermal equilibration time of ~0.6-1.0 fm/c

Hydrodynamics Lessons



✓ Thermal Equilibration:

Large elliptic flow signal implies fast equilibration time of collision system, t ~ 1 fm/c.

x Weakly interacting QGP:

Classic concept of a quark gluon plasma as an ideal relativistic gas with color deconfinement.

✓ Strongly interacting non-hadronic medium:

Fluid-like properties of collision medium indicate significant interactions occur among the particles.

Press Release: "Perfect Liquid"

Contact: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056 — Print-friendly — E-mail Article

RHIC Scientists Serve Up "Perfect" Liquid

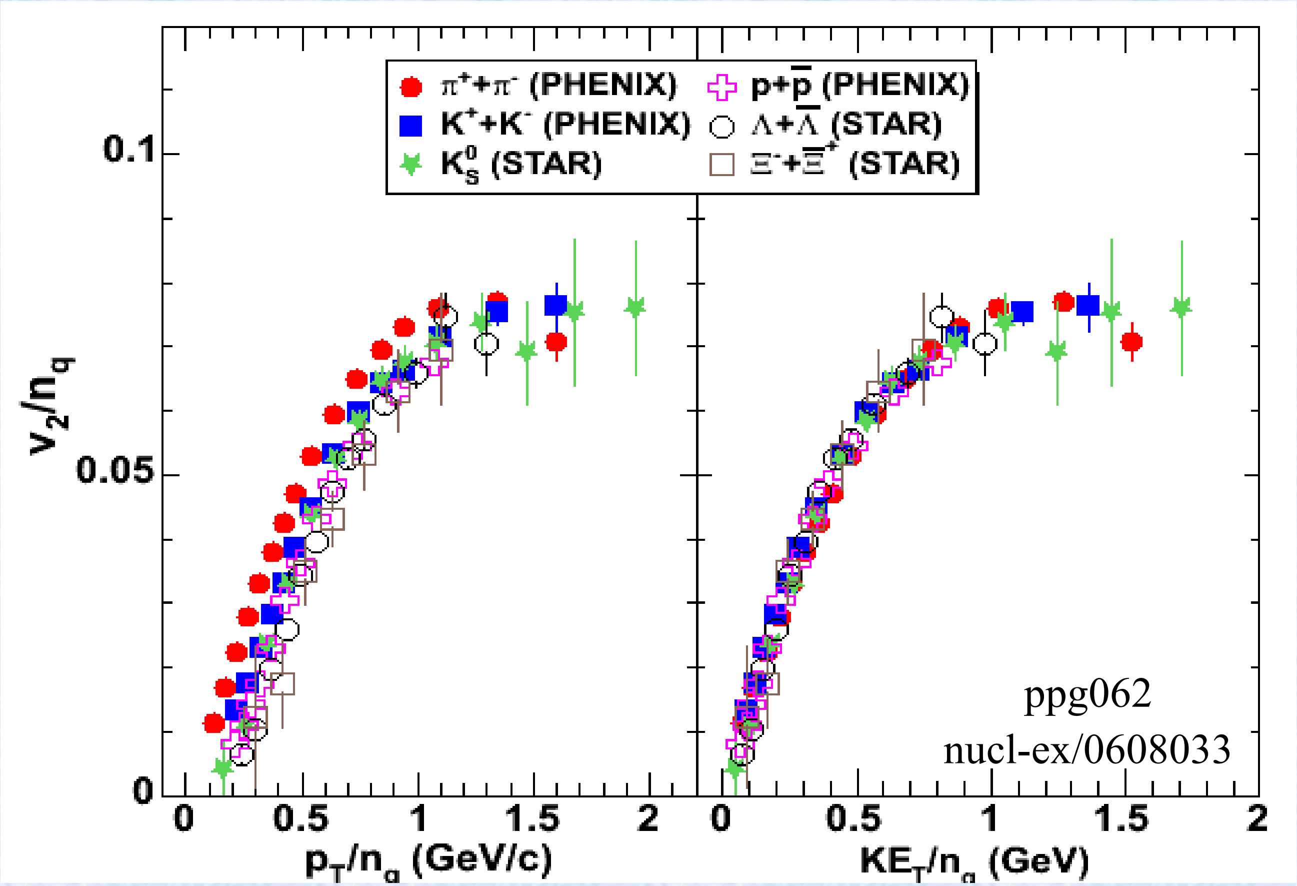
New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

- What is a "Perfect Liquid"?
  - Liquid = a substance that exhibits a readiness to flow with little or no tendency to disperse, and relatively high incompressibility.
  - Perfect Liquid = liquid that exhibits no resistance to flow
- How does this apply to RHIC?
  - Strong elliptic flow observed that is well described by hydrodynamic models
  - Magnitude, particle type up to $p_T \sim 1$ - 2 GeV/c
  - Fast thermalization ($\tau < 1$fm/c)
  - Little or no viscosity

Quark Number Scaling



- Indicates quark-like degrees of freedom in flowing matter for hadrons made of light quarks
- Recombination consistent with observed n_q scaling of v_2

Remaining Questions

- Elliptic flow measurements have been successful at revealing the nature of the collision medium BUT many more measurements remain
  - Heavy quarks:
    - Do they couple to the medium?
  - Quarkonia:
    - Test of regeneration models
  - High p_T π^0's:
    - Parton energy loss as a function of path length in the medium
  - Intermediate p_T direct photons:
    - Test predictions of jet-medium interaction as a function of path length in the medium

- Statistics, Statistics, Statistics…….

Do heavy quarks flow?

Non-photonic Electrons:

Semi-leptonic charm & bottom decays } Signal

Di-electron decays of ρ, ω, ϕ, J/ψ

Kaon decay

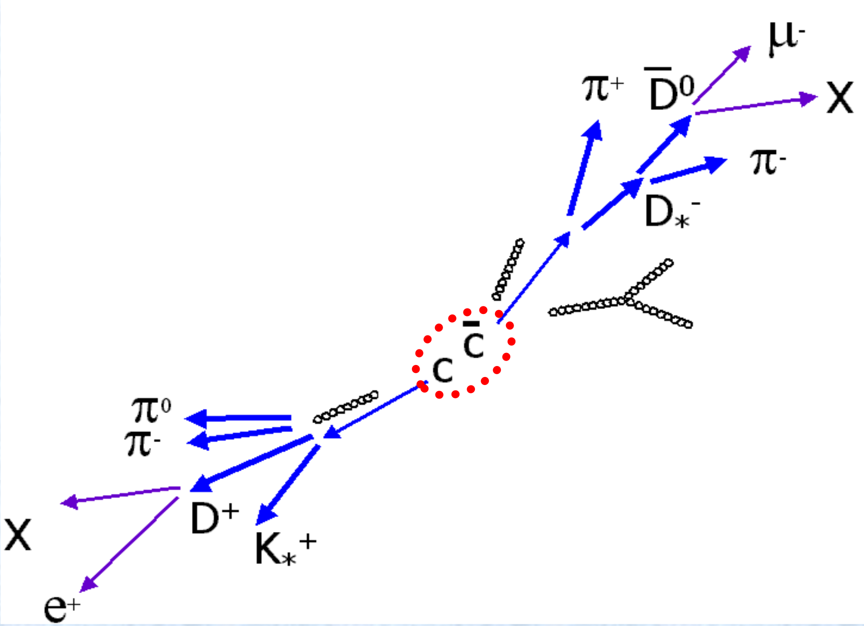
Photonic Electrons:

Dalitz decays of π^0, η, η′, ω, ϕ

Photon conversions

Direct photon (negligible)

} Back ground



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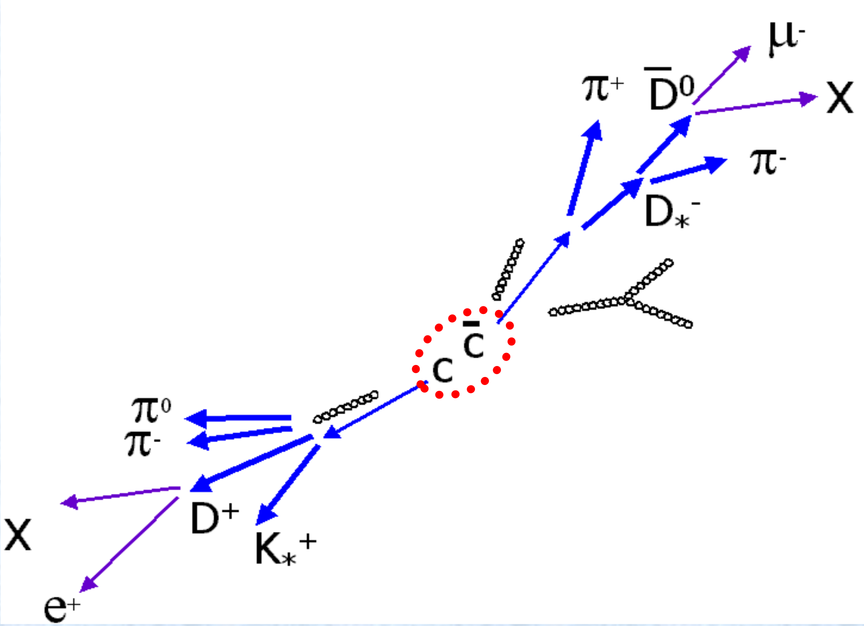

Heavy flavor electron v_2:

Is the single electron v_2 representative of the v_2 of the parent heavy meson?

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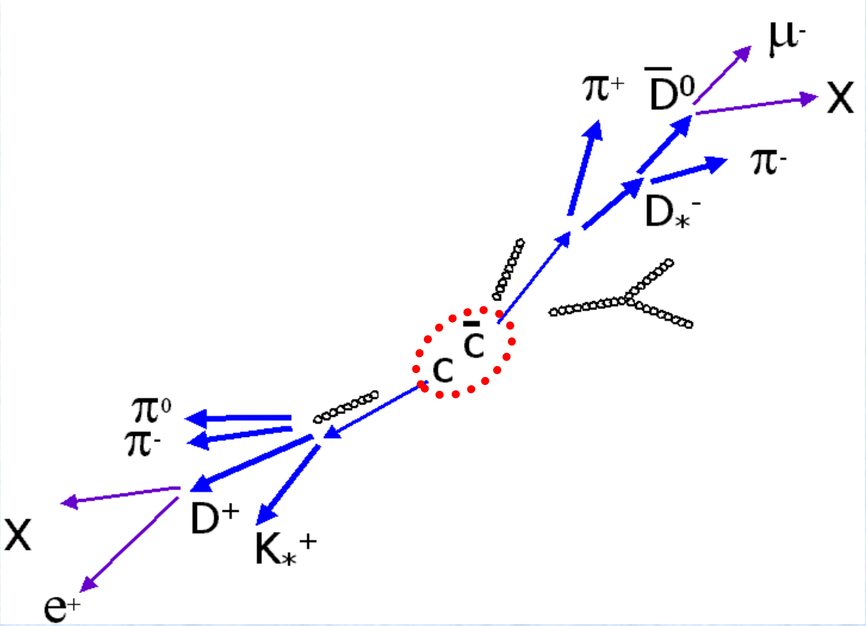

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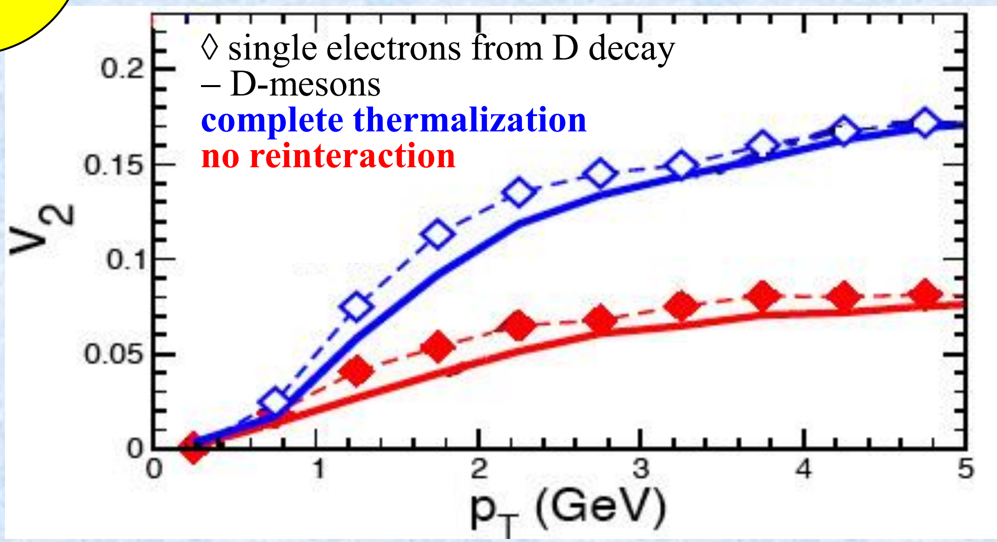


Greco, Ko, Rapp, PLB595, 202, 2004

Possible Scenarios

1. After production heavy quarks do not interact with the medium and eventually fragment in the vacuum

   $v_2 = 0$

2. Heavy quarks suffer in-medium energy loss before fragmenting, but do not flow

   $v_2 \neq 0$

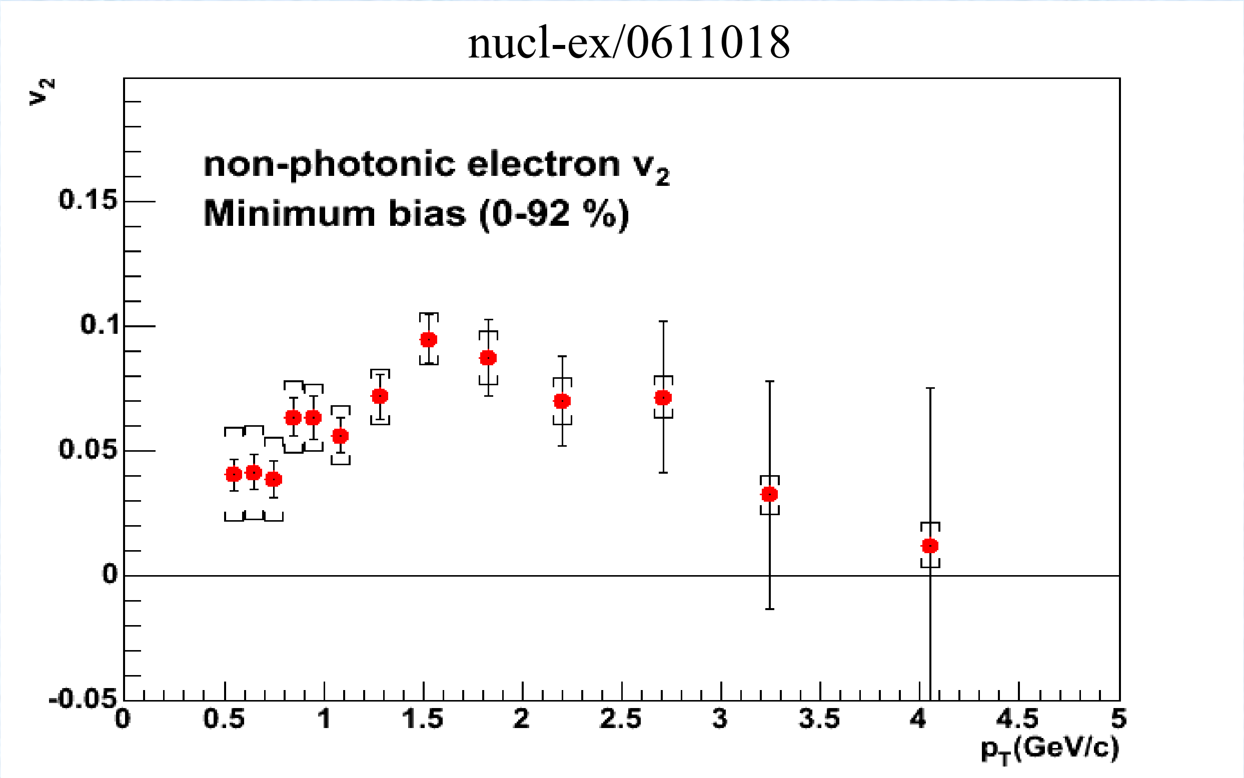
3. Heavy quarks flow in the medium and hadronize via coalescence or recombination

   $v_2 \neq 0$

4. Heavy quarks do not flow with the medium, but hadronize via recombination and pick up v_2 of light quark partner

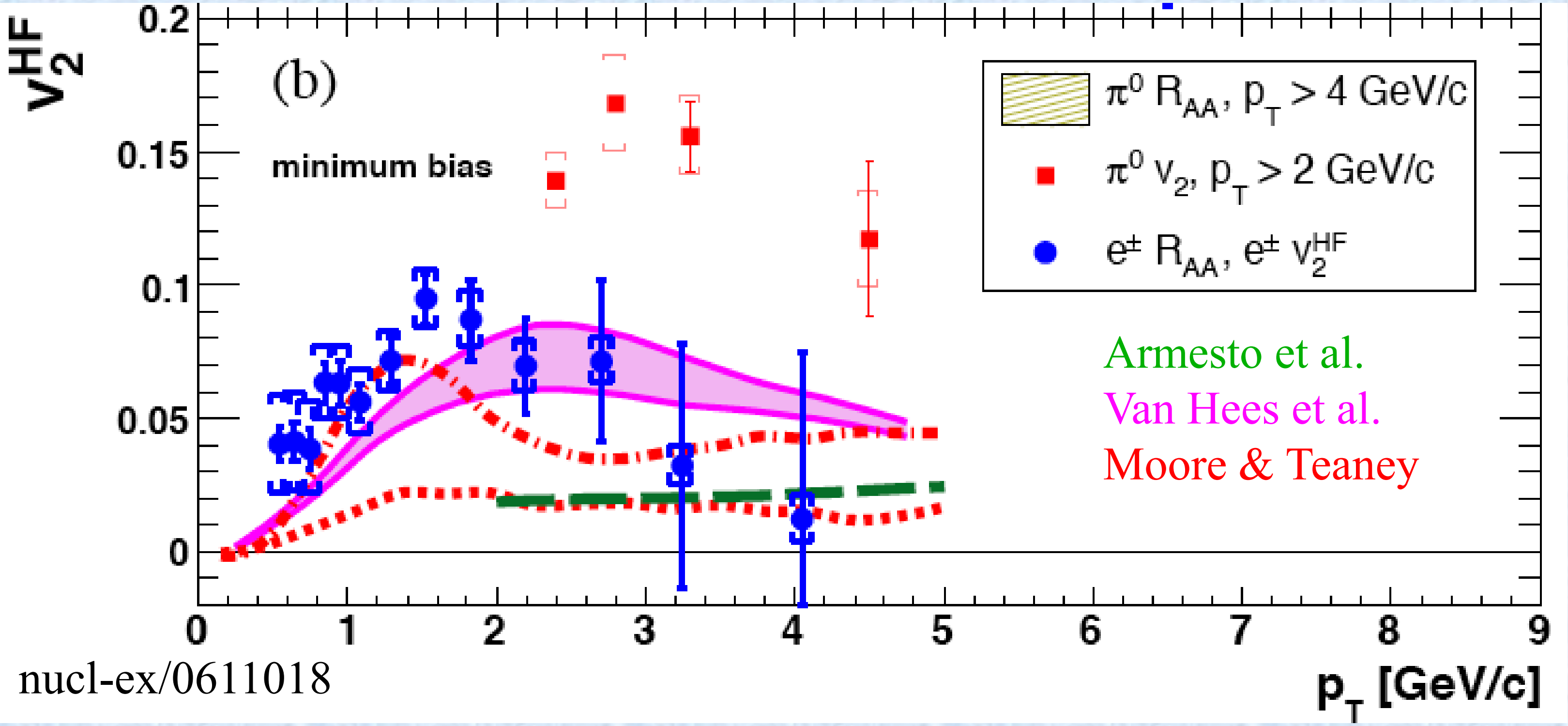
   $v_2 \neq 0$

Do heavy quarks flow?



- Sizeable v_2 seen for non-photonic electrons
- Main source of non-photonic electrons (below 2GeV/c) is D-mesons
- Implies the heavy flavor v_2 is non-zero
- Scenarios 2-4 still possible candidates

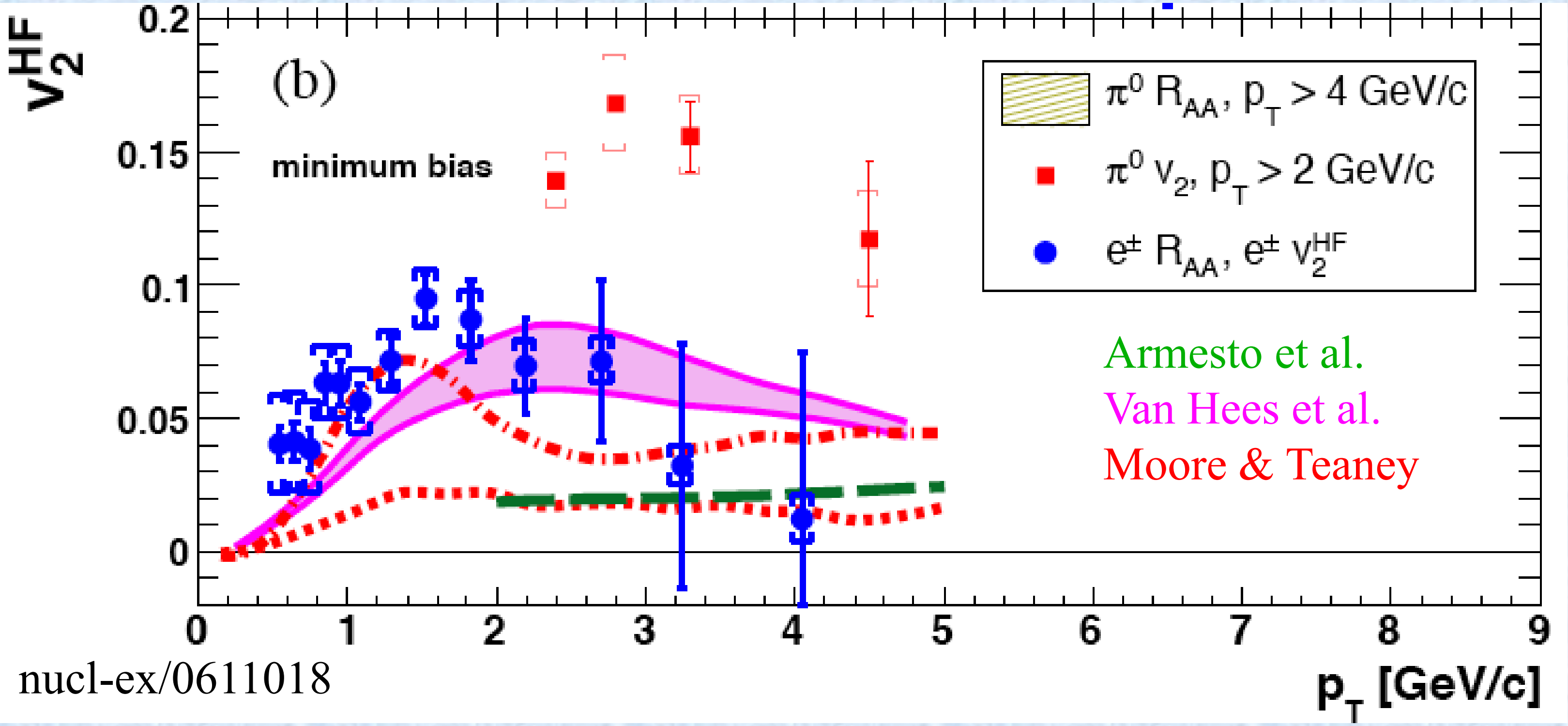
Do heavy quarks flow?



nucl-ex/0611018

- Armesto - (scenario 2)
  - pQCD calculations with radiative energy loss and large transport coefficient
  - v_2 results from path length dependence of energy loss
- Heavy quark transport calculations -
  - Require short relaxation time of heavy quarks
  - Small diffusion coefficient

Do heavy quarks flow?



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Consistent with small values of η/s near quantum bound $\eta/s = 1/4\pi$

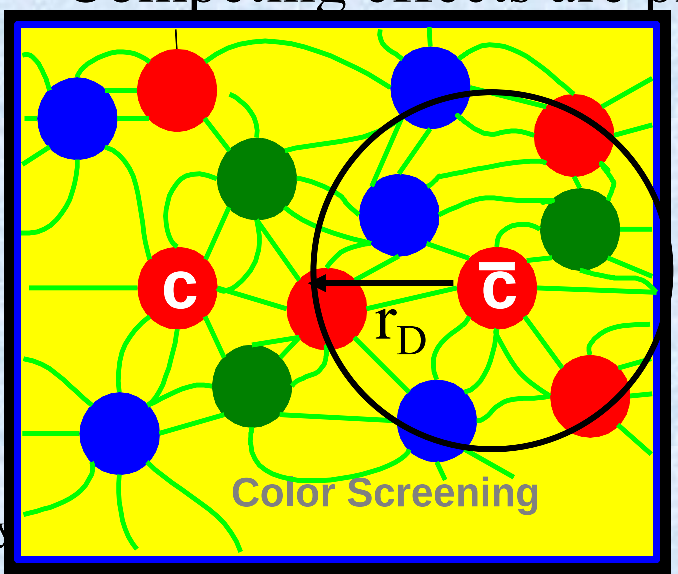
Measurement Limitations

- Scenarios 3&4 still possible:
  - Heavy quarks flow in the medium and hadronize via coalescence or recombination
  - Heavy quarks do not flow with the medium, but hadronize via recombination and pick up v_2 of light quark partner
- Discriminating power of measurement limited by large errors
- Poor statistics at high p_T
  - Region is particularly interesting because it allows access to b-quark through the decay of the B-mesons
  - v_2 of b-quark expected to be small due to large mass

- Improved reaction plane resolution will reduce errors!

Quarkonia

- Quarkonia are of particular interest because….
  - Large mass (J/ψ = 3096.99±0.04 MeV, Y = 9460.37 ±0.21 MeV)
  - Produced during initial stage partonic collisions
  - Medium interactions convey information about the collision environment
  - Measurements of elliptic flow can probe the degree of thermalization of the medium
- In heavy ion collisions only J/ψ is accessible in PHENIX
- Competing effects are predicted to govern J/ψ production



J/ψ color screening

J/ψ recombination

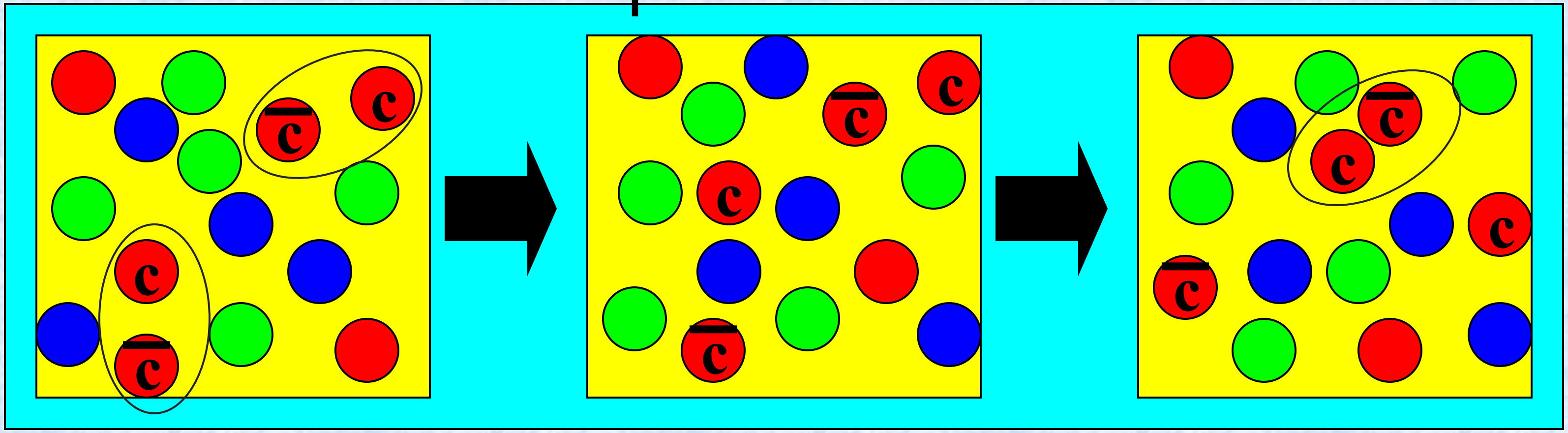
Shadowing

Heavy quark energy loss

Normal nuclear absorption

Etc……

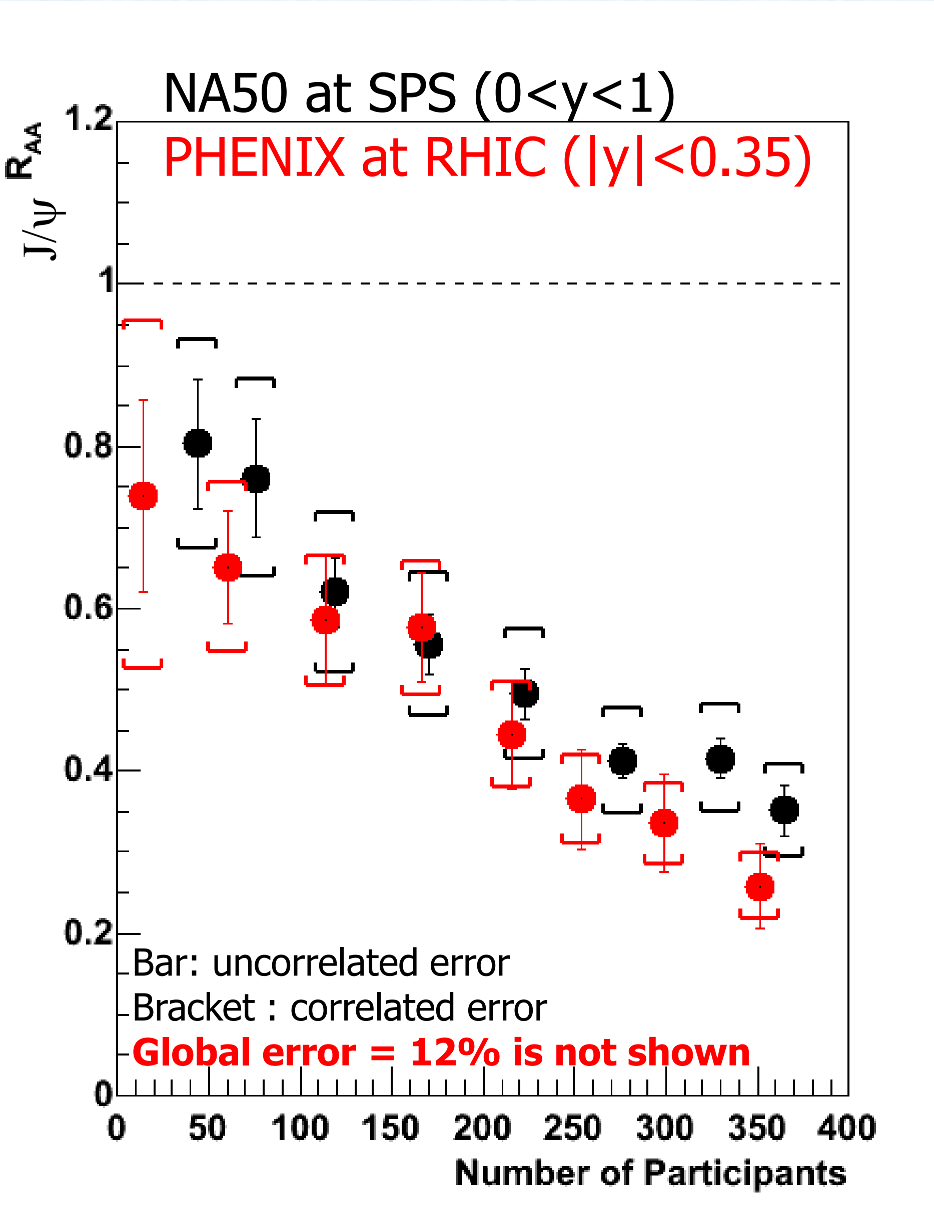
J/ψ Models



- Suppression Models:
  - Assume heavy quarkonia are formed only during the initial hard collisions
  - Subsequent interactions only result in additional loss of yield
  - Suppression of J/ψ yield with increasing collision centrality

- Recombination Models: $c + \bar{c} \leftrightarrow J/\psi + g$
  - In central RHIC heavy ion collisions ~10-40 c-cbar pairs are formed
  - Regeneration of J/ψ possible from independently produced c and cbars
  - Leads to an enhancement of J/ψ yield (or less dramatic suppression)
  - Increased J/ψ yield with increasing collision centrality
  - Narrowed J/ψ rapidity and p_T distributions with increasing centrality

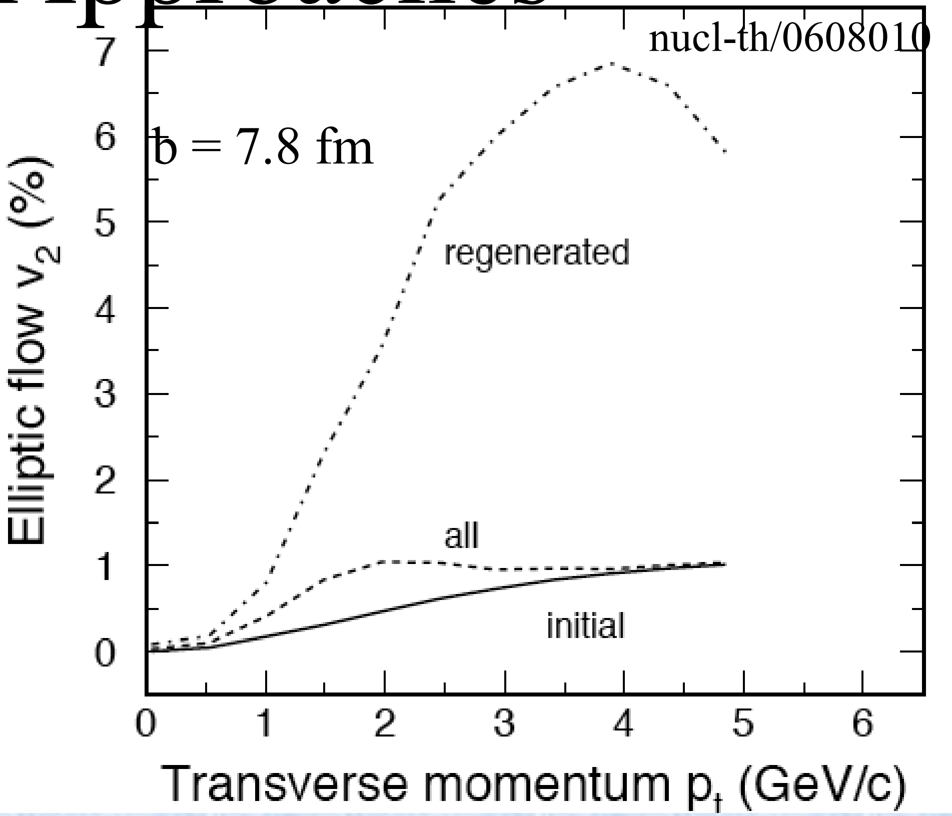
R_{AA} Results



- PHENIX mid-rapidity results show same degree of suppression as observed at the SPS
- Suppression models predict much larger degree of suppression at RHIC energies
- What is the cause:
  - Recombination?
  - Sequential melting?
- J/ψ v_2 can help to distinguish between models

Theoretical Approaches

- Continuous regeneration in collision volume:
  - Weak interaction limit:
    - Charm quarks retain original momentum & spatial distribution
    - No in-medium interaction results in no v_2
  - Strong correlation to medium:
    - Charm quarks thermalized and spatially statistically distributed
    - J/ψ yield still dominated by initial production
    - Small average v_2



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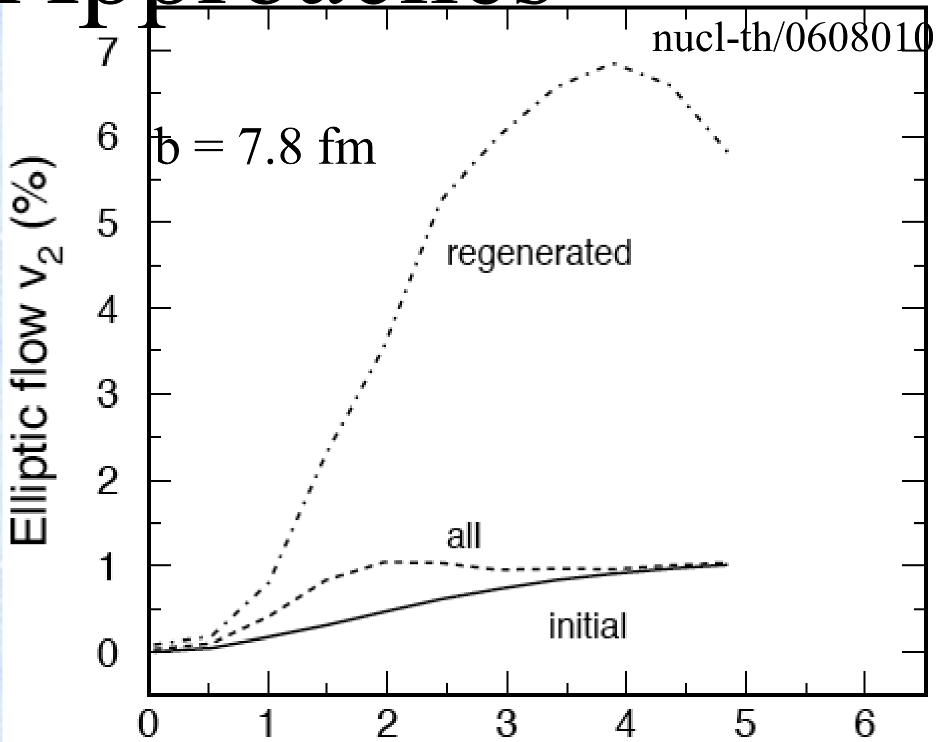
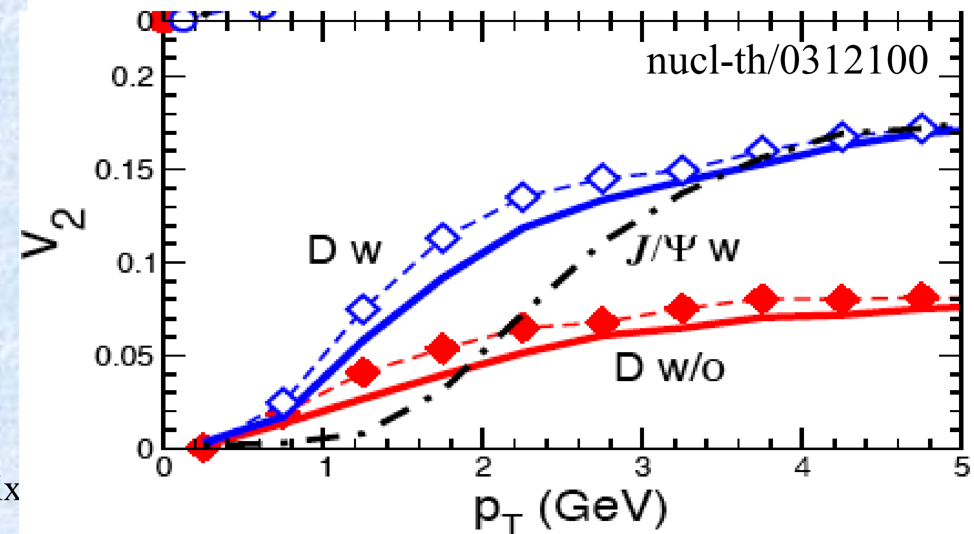
  - Strong correlation to medium:
    - Charm quarks thermalized and spatially statistically distributed
    - J/ψ yield still dominated by initial production
    - Small average v_2
- Regeneration at hadronization:
  - Charm quarks experience complete thermalization
  - No contribution from initially produced J/ψ
  - Large v_2





Do quarkonia flow?

What have we been able to measure so far….

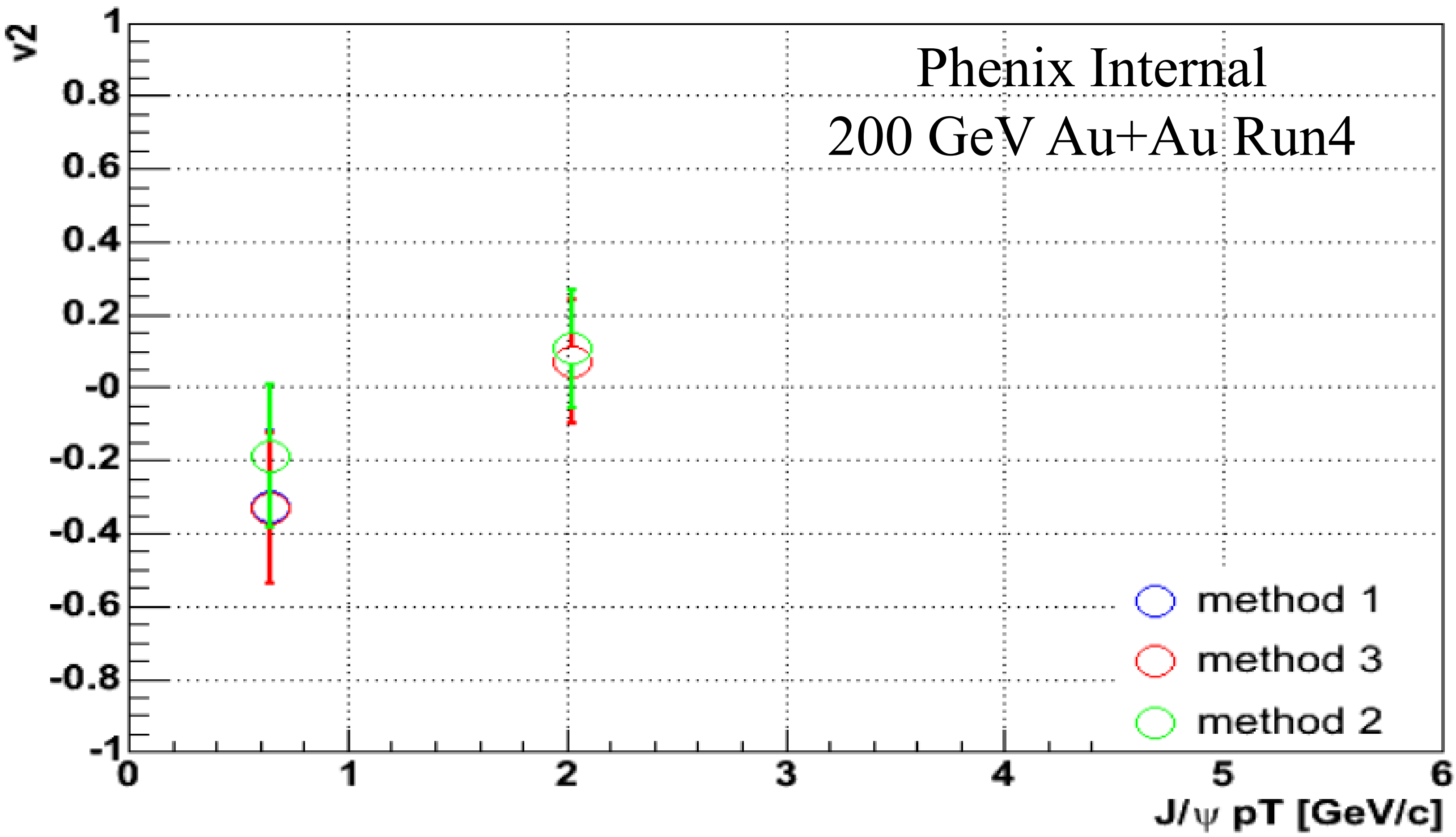
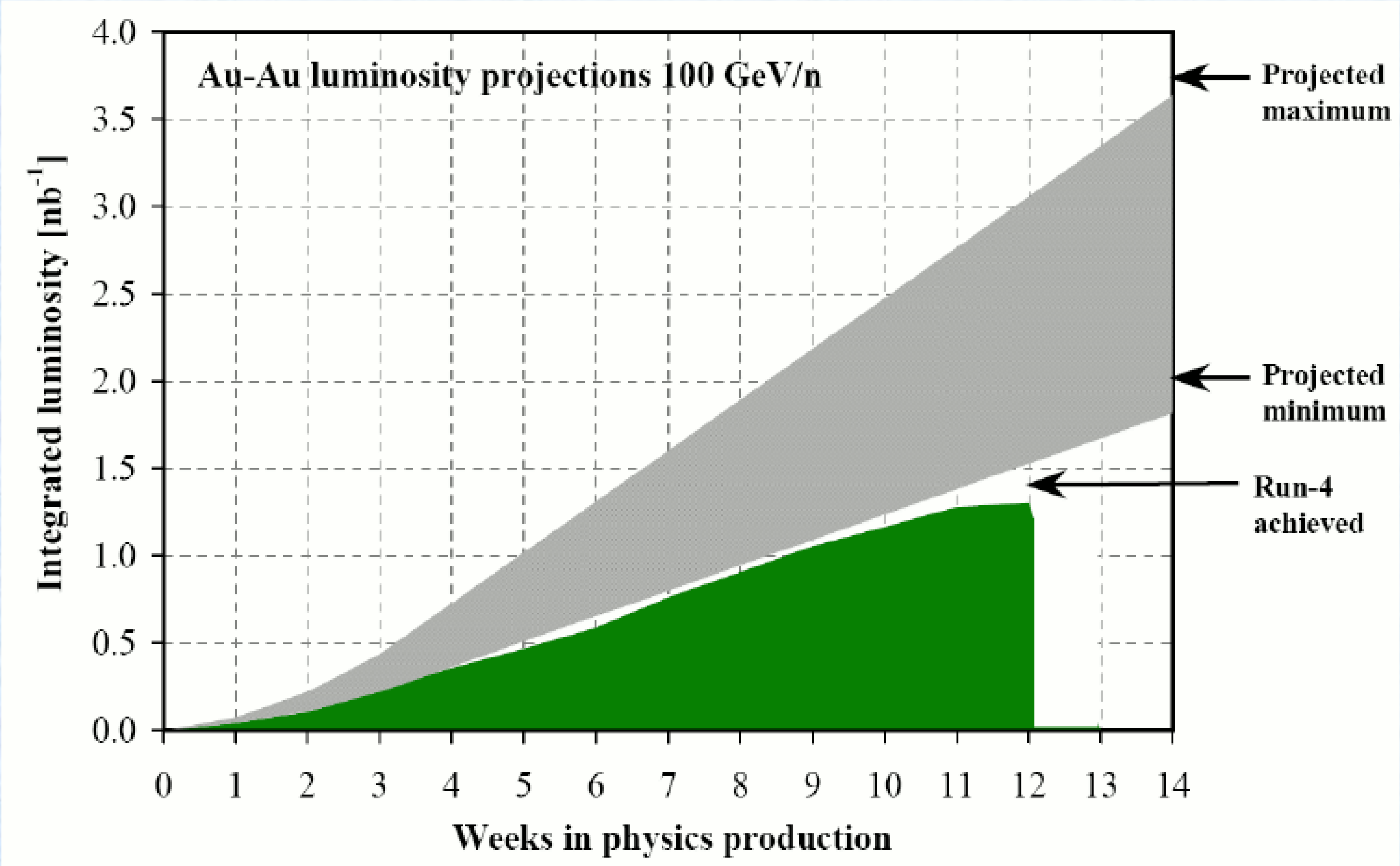


Figure 1.3: The v2 of J/ψ in minimum bias Au+Au collisions.

Run 7 Prospects



- Based on CAD projections for machine performance

Run 7 Prospects

	Run Length (wks)	Mean Luminosity Delivered (nb^{-1})	PHENIX Luminosity (nb^{-1})	PHENIX Events ($x10^9$)
	14	2.56	1.15	7.3
	12	2.16	0.97	6.1
	10	1.71	0.77	4.9
	8	1.29	0.58	3.7
	6	0.92	0.41	2.6
Run4 equiv	4	0.51	0.23	1.5
	2	0.17	0.08	0.5

- Calculations presented at H/L by Tony Frawley
- Assumes PHENIX efficiency factor of 0.45 =

  Up time(70%) * vertex cut loss(80%) * daq dead time (80%)

Run 7 Prospects

- Lets assume we get 14 weeks 200 GeV Au+Au physics:
  - Equivalent to x5 in events
  - Run 4 dimuon J/ψ ~ 4500 ⇒ 22500
  - Run 4 dielectron J/ψ ~ 1000 ⇒ 5000
- What magnitude of statistical error could we expect on a J/ψ v_2 measurement?

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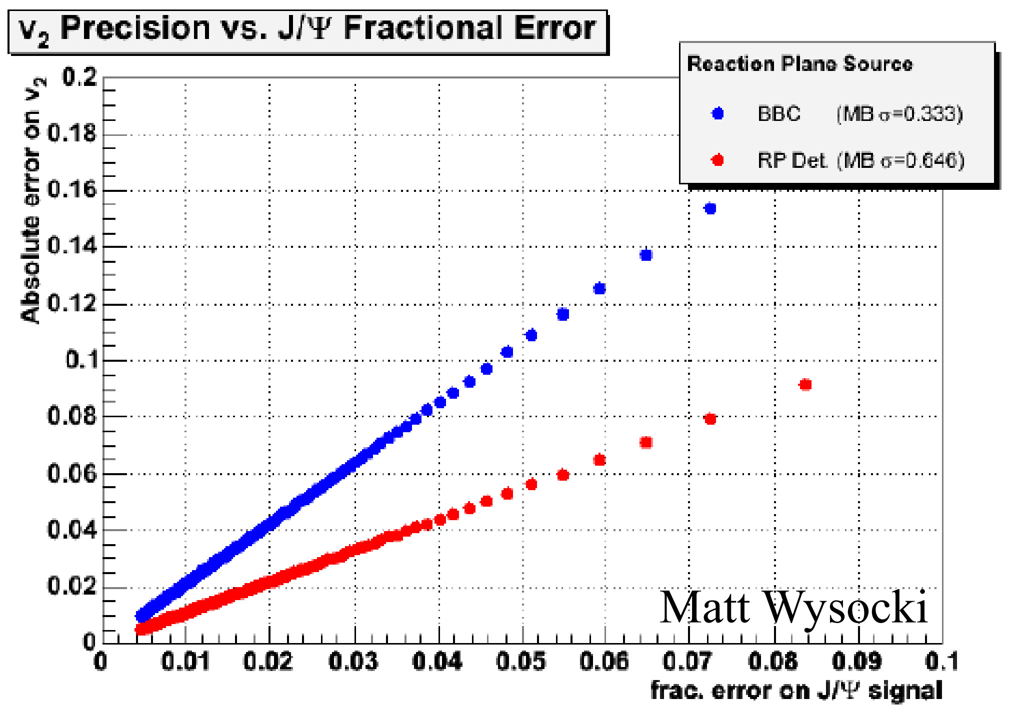
  - The statistical error on the v_2 measurement ~ fractional error on the J/ψ signal
  - Fractional error = (J/ψ stat error) / (J/ψ yield)
  - Depends only on the observed S/B ratio in the J/ψ extraction



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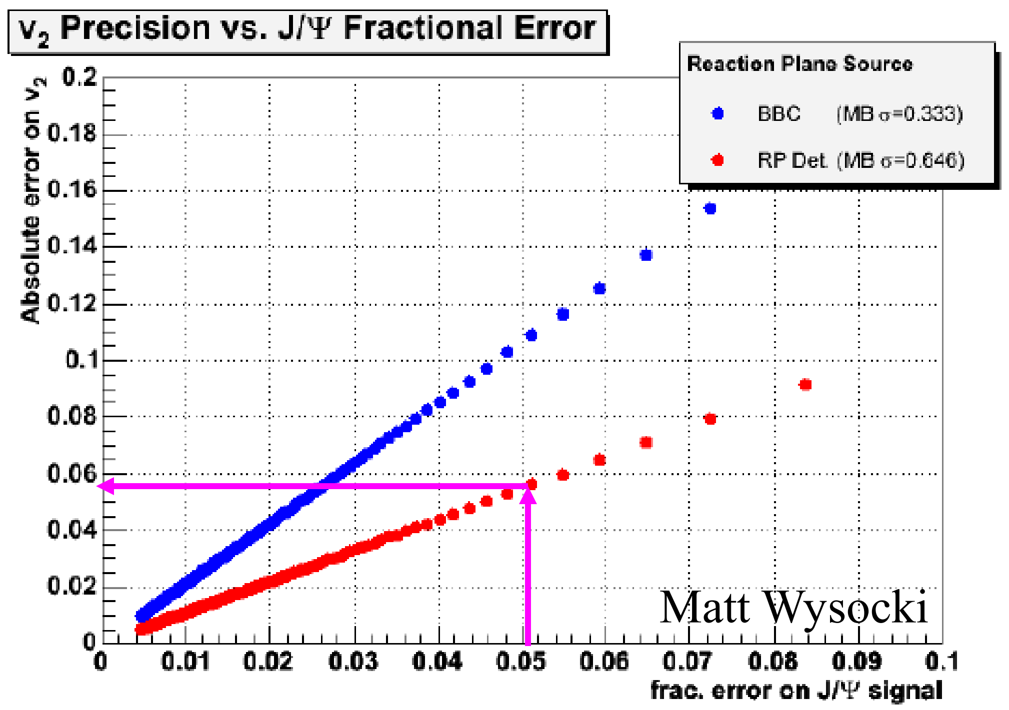
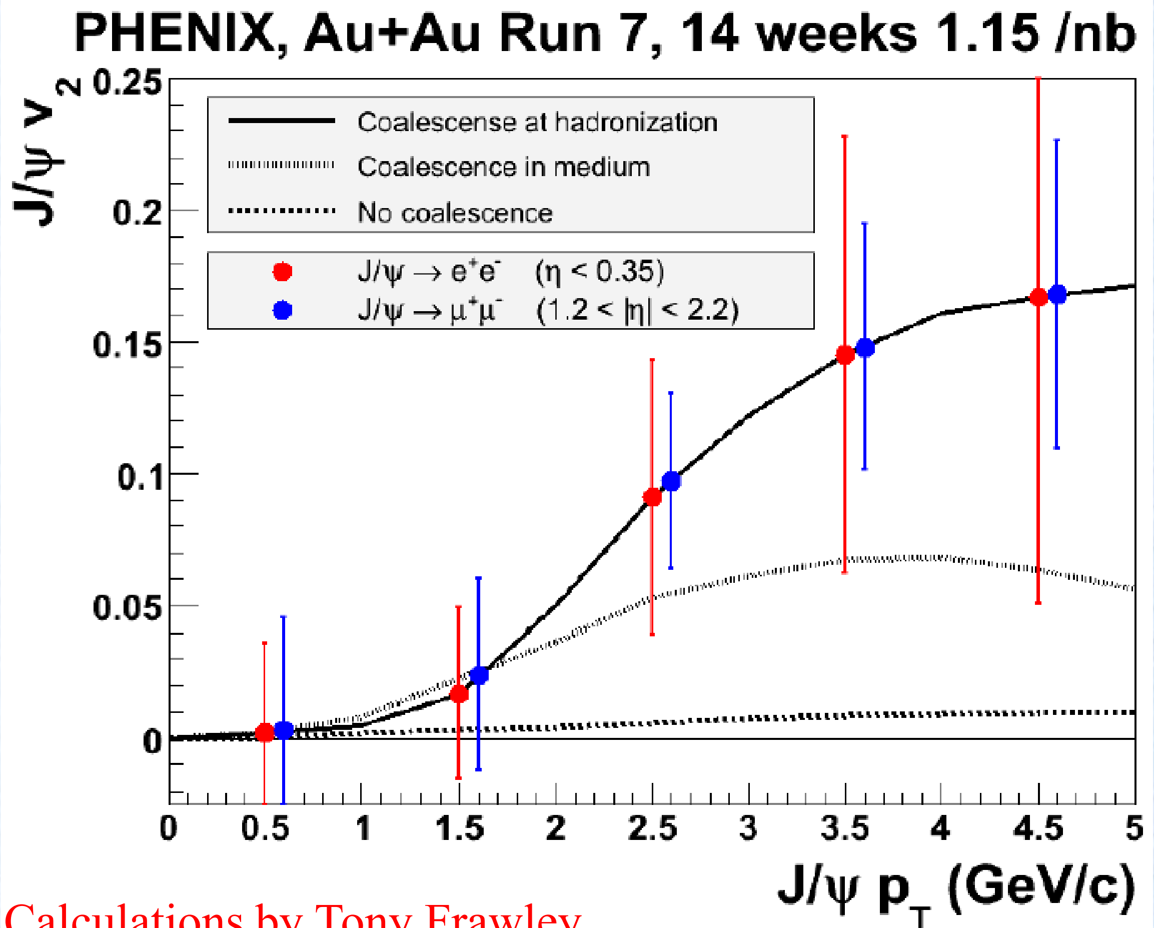


Run 7 Prospects

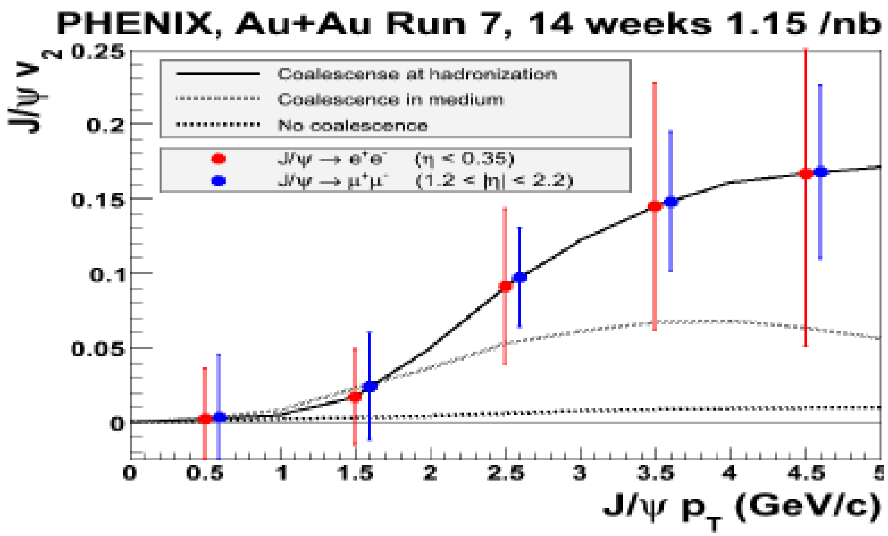


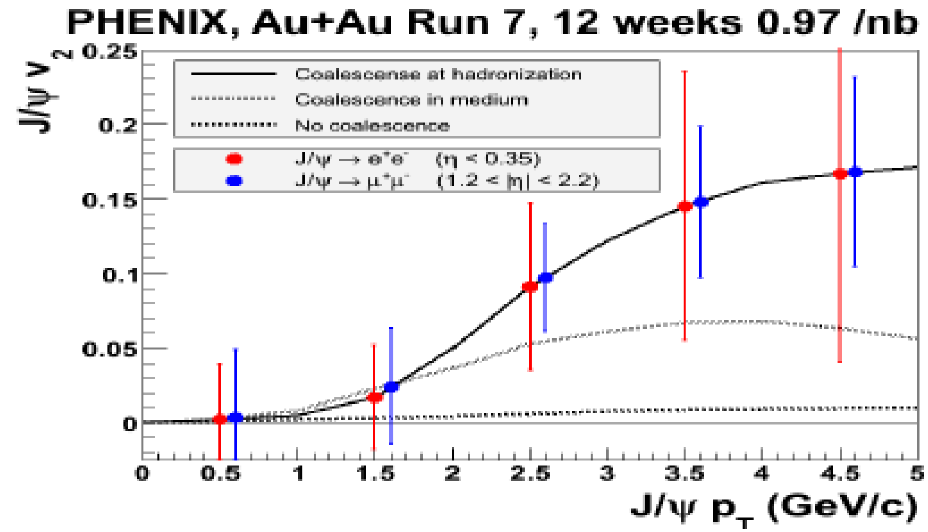
Calculations by Tony Frawley

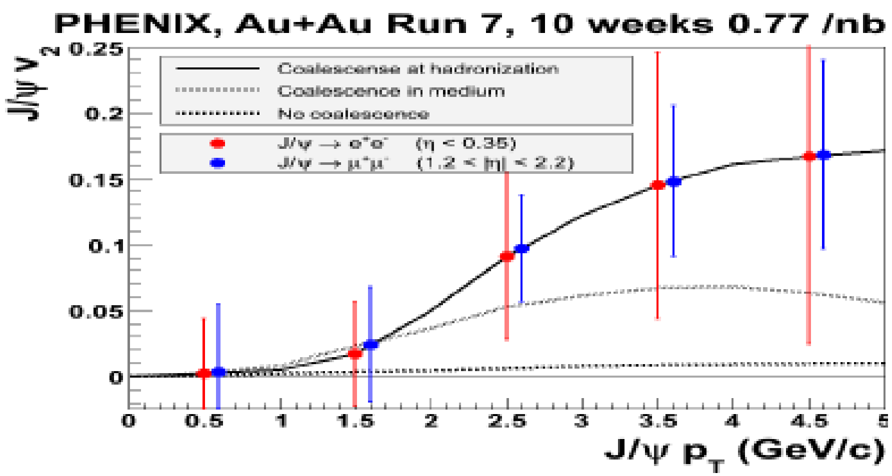
- Statistical error bars indicate expected discriminating power of measurement
- Curves demonstrate range in available model parameterizations
- Point positions are arbitrary => key is errors

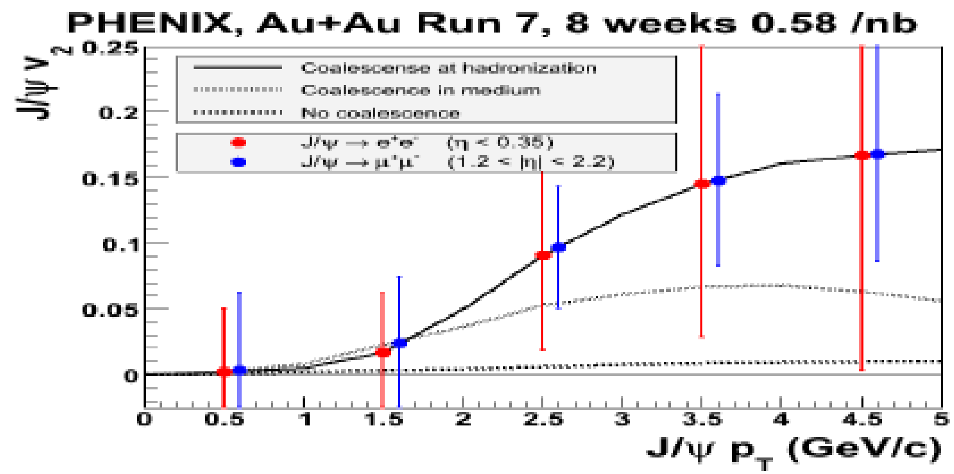
Run Length Dependence

Calculations by Tony Frawley









Questions & Answers

1. What does the reaction plane detector actually measure?
   – Resulting signal is proportional to the original energy deposition in each individual segment
   – Increased energy deposition occurs in those segments aligned with the reaction plane
   – Allows event-by-event determination of reaction plane
2. How is this incorporated into physics analyses?
   – Flow variables measured wrt reaction plane
   – Resolution must be applied as a correction factor to any measurement of flow
3. What do these measurements tell us about the collision medium?
   – Thermal equilibration occurs on short timescales
   – Matter is a strongly interacting partonic medium
   – Future studies will shed light on:
     - Heavy flavor in medium behavior and production/regeneration mechanisms
     - Parton energy loss as a function of path length in the medium from high p_T π^0's
     - Test predictions of jet-medium interaction as a function of path length in the medium with intermediate p_T direct photons

Dependence of v_2 error on v_2 of J/ψ and Background